SCOUR UNDER AIR ENTRAINED JETS BELOW DAMS AND FLIP BUCKETS

by

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Frontispiece - A Flood Flow of 4500 m^3/s being discharged in the form of Free Trajectory Jets, downstream of the Kariba Dam.

(Flows of up to 9000 m^3/s can be discharged via six gated openings in the dam. The head drop from reservoir to tailwater level is approximately 90m. Regular flood discharges from 1962 to 1981 have eroded a plunge pool approximately 70m deep in the massive gneiss bedrock downstream).

To my Father, Francis Osmond Mason and to my Academic Supervisor for six years, Dr. Kanapathypilly Arumugam. Neither of whom lived quite long enough to see this Study concluded.

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The research was carried out, on a part-time basis, through the Department of Civil Engineering at The City University while the author continued his normal work as a Chief Engineer with Sir Alexander Gibb & Partners. It was carried out initially under the supervision of Dr. K. Arumugam, up until his sad death in October, 1986. Subsequently it was carried out under the supervision of Professor J. Chaplin. The writer is grateful to both for their help and guidance.

The writer is also grateful to the Partners of Sir Alexander Gibb & Partners for supporting the Work and to Mrs. A. Parkinson for so diligently typing the final manuscript.

Lastly to my wife, Moira, for putting up with even more evening and weekend work and, in the middle of it all, for presenting me with a second beautiful baby daughter.

DECLARATION

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ABSTRACT

The most popular and accurate form of expression used over the last 50 years for estimating scour under falling jets is:

$$D = K \; q^x \; H^y / d^z$$

There is, however, disagreement between Authors concerning which values should be used for K, x, y and z.

It was surmised by the writer that plunge pool air entrainment could also be a relevant parameter and apparatus was built to examine this assumption. Two dimensional testing without air indicated scour to be independent of head drop (H) and directly proportional to flow (q), such that x = 1.0 and y = 0.0. The introduction of air, to give air/water ratios (β) that a falling jet would entrain naturally, produced values for x of about 0.6 to 0.7 and y of about 0.03 to 0.2. The latter are very close to normally assumed values and it is concluded that such values have been produced by the aeration on previous Authors' models. As aeration is not a simple function of q and H, not allowing for it was bound to produce variable results.

Results from the testing indicated that scour depth varied with aeration to maintain a characteristic force on the particles of bed material. The expression obtained for two dimensional scour was:

$$D = 8.4 \; q \; (1 + \beta)^{0.5} \; h^{0.15} / d^{0.10}$$

It was also reasoned that the expression would have to be modified to allow for the lateral development of plunge pools in the three dimensional case such that (approximately):

$$D = K \; q^{0.5} \; (1 + \beta)^{0.25} \; h^{0.15} / d^{0.10}$$

An analysis of data from previous hydraulic model tests of various dams produced the expression:

$$D = 1.438 \; q^{0.6} \; (1 + \beta)^{0.25} \; h^{0.15} / d^{0.10}$$

with a coefficient of variation of results of 26.8%.

This expression was used to analyse a body of scour data from prototype dams and also gave good results. It is concluded that it represents a new form of expression for calculating scour under jets which seems to be applicable to models and prototypes. In the case of the former it is at least as accurate as any previous expressions. It is concluded that any future plunge pool scour formulae should incorporate an allowance for air entrainment if they are not to be essentially flawed.

One last conclusion from this study is that air entrainments on prototypes may not be significantly different to those encountered on reasonably sized models, given that there may be an upper limit on β of around 2 to 3 and that such figures can easily be approached on models.

LIST OF SYMBOLS

b	Breadth of rectangular jet
Cd	Shape coefficient
cm	Centimetre
D	Scour depth below tailwater level
Da	D due to aerated flow
D act	Actual measured scour depth
D calc	Calculated scour depth
Dpb	Bubble penetration depth
Dw	D due to non-aerated flow
d	Particle size or jet diameter
de	Jet envelope diameter
dj	Long time averaged jet diameter
dm	Mean particle size
dn	Nozzle diameter
d_{90}	Size of bed material of which 90% by weight is smaller
F	Force
g	Acceleration due to gravity
H	Head drop from reservoir to tailwater
Hj	Vertical fall height of jet
Hje	Vertical fall height of jet corresponding to Ve
h	Tailwater depth
K	A constant
k	A constant
Ld	Jet disintegration length
Lj	Jet Length
l	Litres
m	Metres
mm	Millimetres

p	Jet perimeter
Q	Flow
Qa	Air flow
Qab	Air flow dragged by air boundary layer
Qat	Air flow trapped by surface undulations
Qw	Water flow
q	Unit flow
Re	Reynolds number
Rel	Reynolds number based on length of jet
r	Jet radius
s	Jet mean surface disturbance thickness or seconds
t	Time or thickness of rectangular jet
ti	Turbulence intensity
V	Volume scoured ro coefficient of variation
Va	Air volume trapped in pool
Vad	Air volume trapped in pool when Hj = Ld
Vae	Air volume trapped in pool corresponding to V_e
V	Velocity or exponent of acceleration due to gravity, g, in scour equations
V_e	Minimum entrainment velocity
V_i	Instantaneous pressure fluctuation
V_j	Jet velocity
V_n	Nozzle velocity
Wb	Weber number
w	Exponent of tailwater depth, h, in scour equations
x	Exponent of unit flow, q, in scour equations
$\overline{x}_e$	Calculated scour depth divided by Actual scour depth
y	Exponent of head drop, H, in scour equations
z	Exponent of particle size, d, in scour equations

α	Angle of jet impact
β	Ratio of air to water (Qa/Qw)
γ	Surface tension
ρ	Fluid density
μ	Viscocity

In isolated cases some of the above symbols may have been used to represent parameters other than those defined above, or symbols not listed above may have been used. In such cases definitions are given in the appropriate section of text.

Metric (S.I) units have been used in general throughout the text.

CHAPTER 1
INTRODUCTION

1.1 Background Summary

It is customary for the first part of a research study of this nature to review earlier work by others. In this case the writer has, to a large extent, already carried out such a review. Furthermore, summaries of the principle results have been published, (Mason (1982), Mason (1984) and Mason and Arumugam (1985)). Individual aspects of these papers were derived in turn from the one more comprehensive Master of Philosophy Study,(Mason, 1983).

This earlier review into scour under plunging jets served to illustrate both anomalies and gaps in present knowledge, particularly as it applies to practical engineering problems such as energy dissipation at large dam sites. This new study investigates and attempts to explain some of the apparent anomalies and fill some of the gaps.

The matter is introduced in more detail in the remainder of this Chapter.

1.2 Free Jet Energy Dissipation at Dams

Impounding water by the construction of large dams across natural rivers is invariably associated with the need to periodically pass surplus flood waters. Were such releases to be made in an uncontrolled way, significant random erosion damage could be expected downstream. Means are therefore employed to safely dissipate the energy of such flows before the water re-enters the natural river.

The structures built to perform this task are known as hydraulic energy dissipators and can take a variety of forms. The most traditional are hydraulic jump stilling basins, however, increasingly popular alternatives in recent years have featured free trajectory jet action. These include so called flip buckets, ski jumps and free overfalls. They are relatively economic as the structures serve simply to deflect or guide the jet to some point of impact downstream, well clear of the dam and other permanent works. At the point of impact with the river bed, the jet dissipates energy by excavating a scour hole. It is this erosive characteristic of free trajectory jets about which least appears to be known, particularly in quantitative terms.

Upon entering the tailwater the free jet disperses, though a diminishing submerged core may continue for some distance underwater. It is frequently argued that the submerged jet produces dynamic pressure fluctuations on the riverbed, which are transmitted into and along fissures in the rock causing it to break up into blocks. These are then swept away by the flow. The process continues until an ultimate scour depth is reached, whereupon either the jet has insufficient energy at the point of impact to effect further rock breakage, or the rising secondary currents are insufficient to raise the broken material out of the hole.

On prototypes, the matter is complicated by rock being tumbled around in the scour hole causing further erosion, while itself degrading to a smaller and more easily removable size. Furthermore, the tailwater becomes a mixture of water, entrained air and scoured bed material swirling around in secondary currents induced by the main jet. This, together with the dispersion of the main jet and the rapidly changing geometry of the scour hole, has made the theoretical analysis of such scour very difficult. Research to date, has, therefore concentrated on developing empirical formulae for ultimate scour depth based on experiment and observation.

Where laboratory tests have been carried out, either as models of proposed dissipators or for research purposes, gravel has generally been used as the bed material. This will scour to a much greater lateral extent than rock owing to its flatter angle of repose and attempts have been made in the past to compensate for this by binding the gravel with clay, wax, neat cement or other cohesive materials. Such modelling techniques were also reviewed as part of the earlier studies,(Mason 1983 and Mason 1984).

1.3 Previous Scour Formulae

It was mentioned above that research to date has concentrated on developing empirical formulae for estimating ultimate scour depth based on experiment and observation. The previous studies,(Mason (1983) and Mason and Arumugam (1985)), reviewed over 30 formulae proposed during the past 50 years for calculating ultimate depths of scour under free falling jets. Original sources for these formulae are listed in the bibliography. The formulae were each used to process a body of scour data from prototypes and models of prototypes, which were collected by the writer from individuals and agencies worldwide. Full details of these scour cases are given in Appendices B and C of the previous study,(Mason 1983).

For the purpose of analysis the model and prototype data were processed separately. The accuracies of the formulae were assessed by comparing the depths predicted by the formulae with the actual measured depths. The mean value $\bar{x}_e$, of calculated scour depth divided by measured scour depth, was obtained for each formula together with the coefficient of variation, V, of the results. The principal conclusions from these studies can be summarised as follows:

* The most accurate, general form of expression proposed to date for estimating the depth of scour under free falling jets is:

$$D = K \frac{q^x \quad H^y}{d^z}$$

where

D	=	depth of scour from tailwater level to base of the scour hole
K	=	Coefficient
q	=	Unit discharge
H	=	Head drop from reservoir level to tailwater level
d	=	Characteristic particle size of bed material
x, y, z	=	Exponents for q, H and d respectively.

Depending on the values adopted for K, x,y and z this can give coefficients of variation of results in the order of 30% for both models and prototypes. A list of values for K, x,y and z proposed by various Authors is given in Table 1.1.

The most accurate form of this expression for estimating scour depth on models was that proposed by Sofrelec, 1980, where:

$$D = 2.30 \quad q^{0.60} \quad H^{0.10}$$

This gave a coefficient of variation for model data of 29.47%, with $\bar{x}_e = 1.15$.

The most accurate form of this expression for estimating scour depth on prototypes was that proposed by Damle 1966, where:

$$D = 0.543 \quad q^{0.50} \quad H^{0.50}$$

This gave a coefficient of variation for prototype data of 33.16%, with $\bar{x}_e = 1.06$.

Author (1)		K (2)	x (3)	y (4)	z (5)	d (6)
Schoklitsch	1932	0.521	0.57	0.20	0.32	d_{90}
Veronese -(A)	1937	0.202	0.54	0.225	0.42	d_m
Veronese -(B)	1937	1.90	0.54	0.225	0	-
Eggenburger	1944	1.44	0.60	0.50	0.40	d_{90}
Hartung	1959	1.40	0.64	0.36	0.32	d_{85}
Franke	1960	1.13	0.67	0.50	0.50	d_{90}
Damle -(A)	1966	0.652	0.50	0.50	0	-
Damle -(B)	1966	0.543	0.50	0.50	0	-
Damle -(C)	1966	0.362	0.50	0.50	0	-
Chee and Padiyar	1969	2.126	0.67	0.18	0.063	d_m
Bisaz and Tschopp*	1972	2.76	0.50	0.25	1.00	d_{90}
Chee and Kung	1974	1.663	0.60	0.20	0.10	d_m
Martins -(B)	1975	1.50	0.60	0.10	0	-
Taraimovich	1978	0.633	0.67	0.25	0	-
Machado	1980	1.35	0.50	0.3145	0.0645	d_{90}
SOFRELEC	1980	2.30	0.60	0.10	0	-
INCYTH	1981	1.413	0.50	0.25	0	-

*Different form of Expression

TABLE 1.1 Coefficientsfor use in the Expression

$$D = K \frac{q^x H^y}{d^z}$$

* From the values of x, y and x in the various formulae tested it appeared that there is general agreement for a value of x of about 0.5 to 0.6. Values for y and z, however, vary considerably. Moreover, the values for y which gave the most accurate results for model data (expressed in terms of the co-efficient of variation of the results) were not those which gave the most accurate results for prototype data and vice versa.

  This is illustrated in Figures 1.1, 1.2 and 1.3 which plot coefficients of variation of scour prediction results against values of x, y and z.

1.4 New Formulae

The previous studies by the writer finished with the results described in 1.3 above. As a first step in this study it was decided to empirically develop a new formula which would better fit the existing model and prototype data. Two formulae resulted and, although not forming part of the earlier studies, were published as a convenient ending to two of the writer's earlier papers,(Mason (1984) and Mason and Arumugam (1985)) . The development of these formulae is described below:

In the previous studies, one of the formulae processed was that by Jaeger, as reported by Hartung (1959). Jaeger included tailwater depth as an additional factor. The analysis of data using Jaeger's formulae yielded an accuracy greater than could have been expected from his exponents for q, H and d alone, hence it can only be assumed that the improvement stemmed from his inclusion of tailwater depth as an additional factor. For this reason it was also incorporated into the writer's expression.

The acceleration due to gravity was also incorporated making possible a dimensional balance and giving the form of expression:

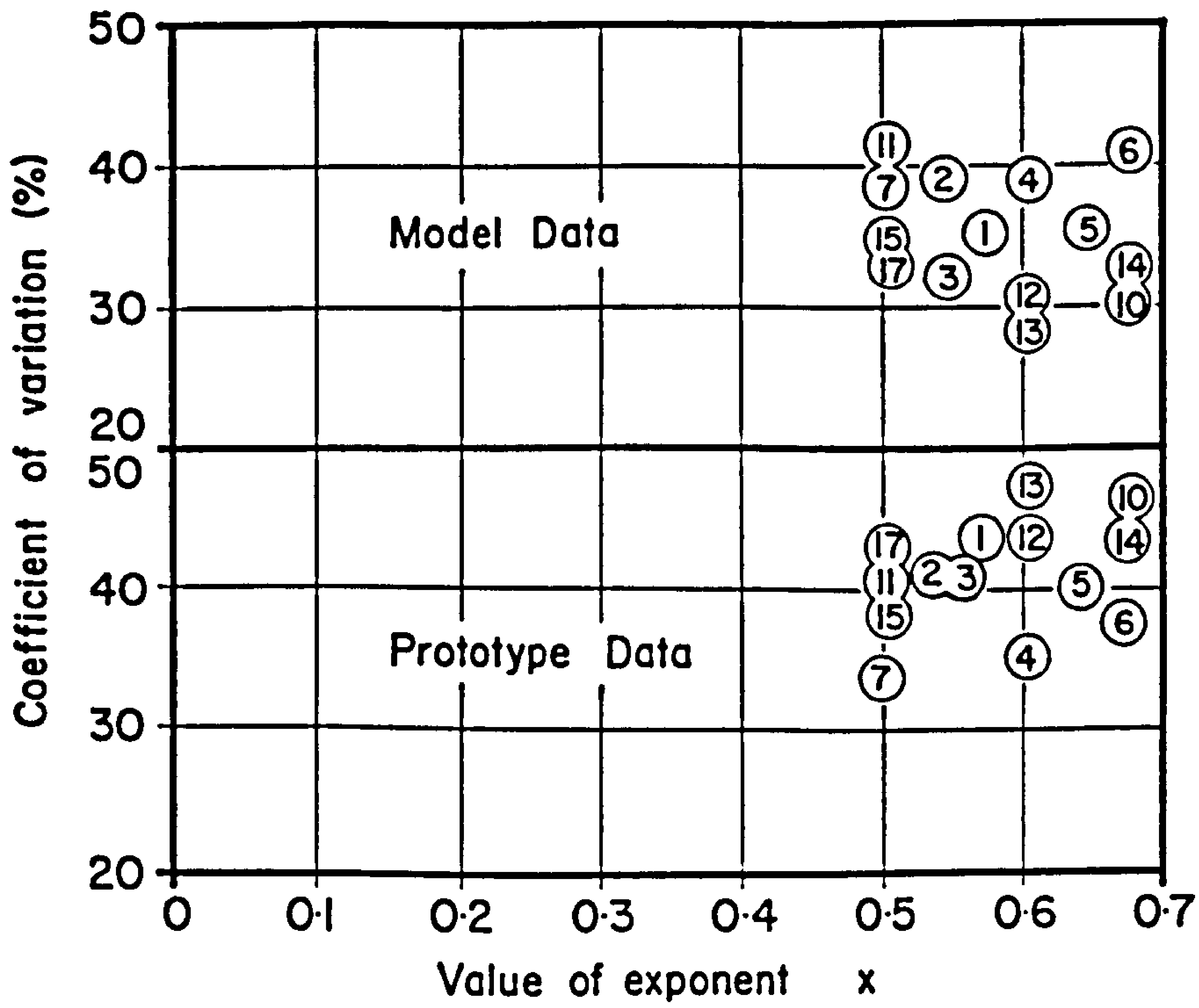


FIGURE 1.1 Coefficients of Variation Plotted against values of Exponent x.

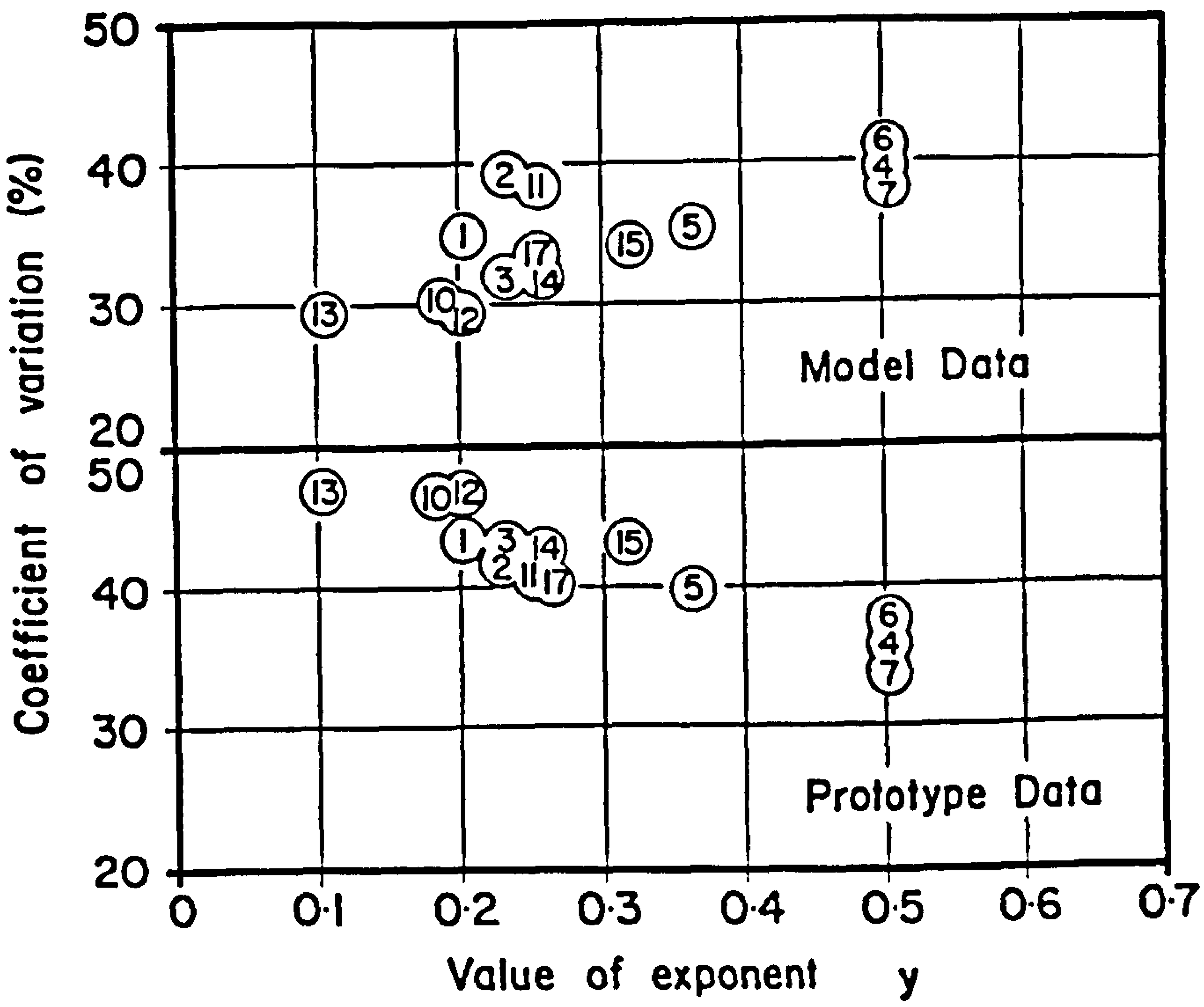


FIGURE 1.2 Coefficients of Variation Plotted against values of Exponent y.

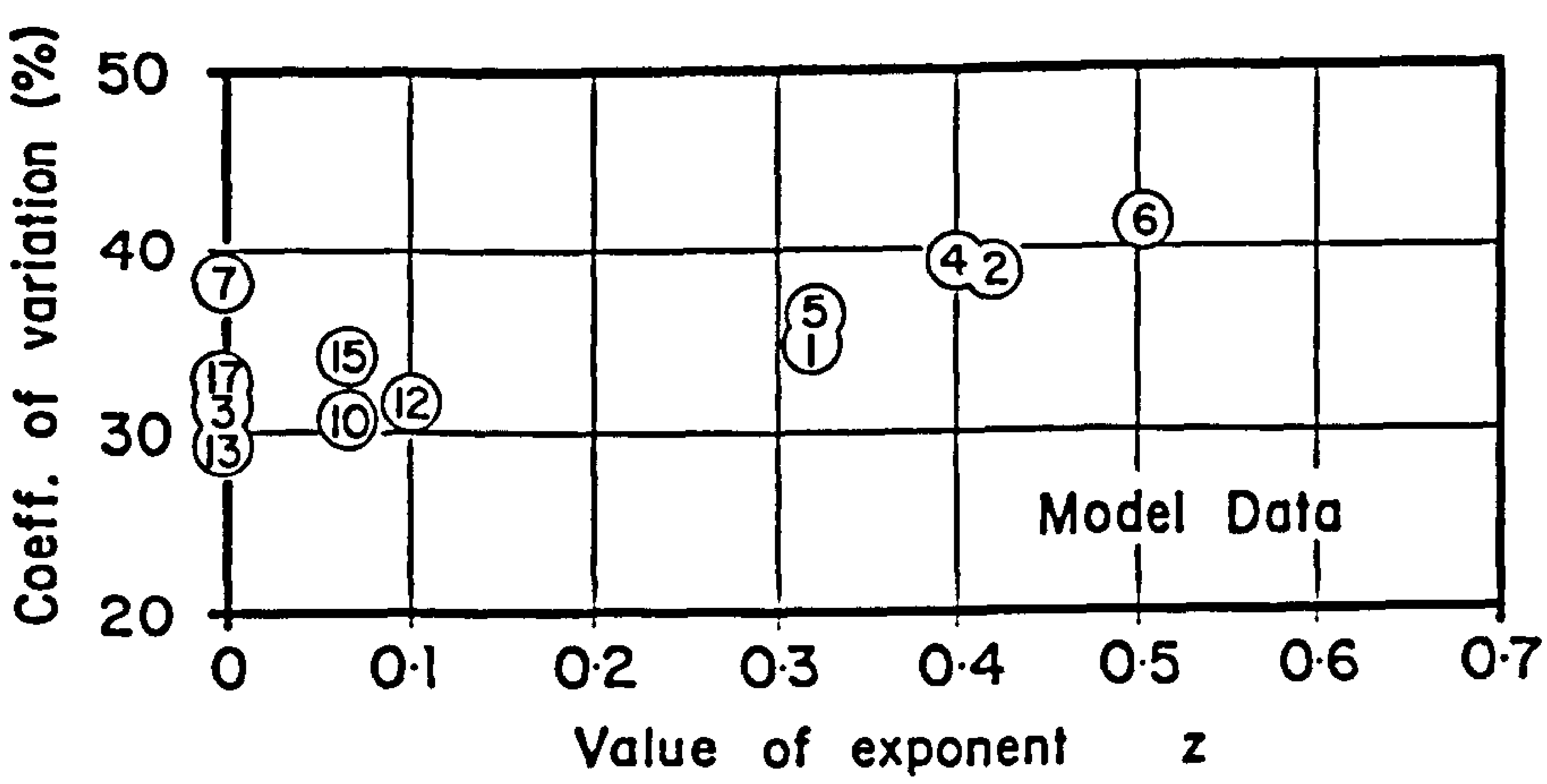


FIGURE 1.3 Coefficients of Variation Plotted against values of Exponent z.

$$D = K \frac{q^x \; H^y \; h^w}{g^v \; d^z}$$

This basic formula was used to process the same sets of data as before, and the appropriate values of x, y, w and z were obtained by varying each in turn to minimize the coefficient of variation of the results. The value of v was then chosen to give an overall dimensional balance and K was chosen to give a mean value for $\bar{x}_e$ close to unity. Using this approach for the model data only yielded the equation:

$$D = 3.27 \frac{q^{0.60} \; H^{0.05} \; h^{0.15}}{g^{0.30} \; d^{0.10}}$$

In this expression d_m was used rather than d_{90}.

It was particularly pleasing to discover that the above formula also gave a Froude number balance so that:

$$1.5\,x + y + w - z = 1.0$$

For model data, the formula gave an $\bar{x}_e$ value of 1.00, and a coefficient of variation of 25.4%. As might be expected from earlier work, however, the formula did not give very good results for prototype data. The previous studies had shown the need to vary the exponentials x and y to give low coefficients of variation for both model and prototype results. In order to maintain a Froude number balance this was done so that the variation in the value of x always equalled two-thirds of the value of y. Various expressions were tried; the ones finally selected were those which produced the best optimization for the co-efficients of variation for both model and prototype data. In order to obtain acceptable x values for both models and prototypes, however, it also proved necessary to use a variable value for K. This was obtained by an essentially trial and error process. For a complete model and prototype expression it was found that:

$$K = 6.42 - 3.10\ H^{0.10}$$
$$v = 0.30$$
$$w = 0.15$$
$$x = 0.60 - H/300$$
$$y = 0.05 + H/200$$
$z = 0.10$ (with an assumed constant value for d of 0.25 m for prototypes)

These values produced coefficients of variation for model results of 25.3% and for prototypes of 30.1%, and corresponding values for $\overline{x}_e$ of 1.01 and 1.07 respectively.

As mentioned before, the development of the above new formulae was carried out as part of this study. It did not form part of the earlier M.Phil. submission.

1.5 The Next Step

The exercises described in 1.3 and 1.4 above identified the most accurate forms of expression proposed to date for calculating the depth of scour under plunging jets. They also took this form of expression to the limit of its accuracy in terms of the data available for comparative checking.

It might be argued that in order to take the matter still further, a rigorous attempt should be made to review the factors and processes governing the scour. Such factors and processes traditionally considered as fundamental include the nature of jet diffusion within the plunge pool and the distribution and fluctuation of pressure over the mobile bed.

In fact such aspects have been tested and analysed in the past without, it would appear, producing scour depth formulae any more accurate than the ones already discussed.

The definitive work often referred to when considering the dispersion or decay of jets under water is that by Albertson et al (1948). More recent studies,(Ervine, 1985 and 1986_2), have demonstrated that the more realistic case, of a plunging jet also entraining air, is in fact far more complex. Indeed it is a subject now being actively researched in its own right and with more information required in the case of high velocity jets. It might also be argued in the case of scour holes, that the confines of the hole and the need to accommodate return currents could significantly affect the geometry and nature of jet dispersion. Also that this would be a changing function as the hole develops.

At least two sets of authors, Cola (1965) and also Hartung and Hausler (1973) have considered scour depth to be a function of jet diameter or thickness.

They argued that this would be the main parameter governing the decay length of jets and that this in turn must govern their potential to effect scour. It was found in the previous M.Phil. analysis, however, that jet thickness was not a reliable parameter for assessing scour.

Another aspect on which authors such as Hartung (1959) have commented is that scour can be limited not only by the ability of the jet to dislodge material from the bed but also by the ability or otherwise of secondary return currents to remove that material to a point beyond the limit of the scour hole. Both Doddiah et al (1953) and Kobus et al (1979) refer to scour phases where deep, steep sided pockets occur rapidly by jet injection. Material becomes trapped in the rapidly circulating return currents and this effectively limits the further progress of scour.

Pressure over the wall jet region has been reviewed and studied by McCreath (1977) among others. It is difficult to assess precisely its effect on mobile bed scour in practical terms, given the rapidly changing geometry of scour holes. Furthermore, Kobus et al (1979) have demonstrated that there are at least two different phases or types of scour under jets, with the mobile bed behaving differently in each. They also emphasize the effect of jet injection into the bed which must render suspect any attempts to relate scour to the behaviour of wall jets where the characteristics of these have been established by tests using solid boundaries.

The work by McCreath (1977), with results later summarised by Francis and McCreath (1979) represented a direct attempt to relate mobile bed scour to the effect of the wall jet. It attempted to demonstrate that the volumetric rate of scour could be linked to the unit jet power over the bed. It concluded that such a link did exist and hence that local scour could be linked to the more general stream power theory of Bagnold (1977).

One interesting possibility if McCreath's thesis is correct is that in the expression:

$$D = K \; q^{x} \; H^{y}$$

the exponents x and y must be equal as power is a direct function of q and H. Furthermore if as McCreath claimed:

$$\frac{dV}{dt} = f \; (\text{power})^{3/2}$$

where $\frac{dV}{dt}$ = volumetric scour rate

and Power = Power in excess of that required to initiate movement

and if $D \propto \sqrt[3]{V}$

then $\frac{dD}{dt} = f \; (\text{Power})^{1/2}$

If maximum scour is further assumed to be proportional to rate of scour, then this in turn would imply:

$$D = K \ (q \ H)^{0.5}$$

which is in fact the expression proposed by Damle et al (1966) and which gave the most accurate results for analysising prototype scour in the earlier studies, See 1.3 above.

This coincidence led the writer to carry out a detailed analysis of the scour at Kariba dam in relation to the power of the incoming jet. It was published during the course of this study,(Mason and Arumugam, 1985). With hindsight the results were really inconclusive given that the associated head drop varied very little at Kariba compared to the flow. The stream power analogy also leaves unresolved the fact that at model scales, where conditions for assessing scour are in fact the most controlled, it would appear that q clearly dominates H in its effect on scour.

This last point raises yet another possibility. As mentioned in 1.4 above, it was found that the writer's model formula noticeably over-estimated prototype scour. This, however, was based on 'lines of best fit' through both model and prototype data points. In the case of the model data this was probably a reasonable approach. In the case of the prototypes it could be argued that many of the cases recorded might not have had time to develop fully and therefore the appropriate line should perhaps be an upper envelope rather than a mean. This, in turn, could imply that the model formula is essentially correct for prototypes as well and that the apparently significant effect of H suggested by the earlier studies simply reflected the pattern of the available prototype data points.

There are clearly many interrelated factors apparently governing the scour process with the precise effects of many parameters such as q and H still to be clearly established. In order to make further progress in the matter it was decided to take a fundamental over view to see if any significant aspects might to date have been omitted.

It was concluded by the writer that a useful insight might be gained by introducing and quantifying the effect of air as an additional parameter. Although this had never been done before in any critical way there were various reasons which suggested that it's effect might be significant:

Most workers who have carried out model tests on scour under jets have allowed jets to plunge onto mobile beds and have then systematically varied each parameter in turn in order to quantify its effect. It is therefore surprising that such differences have emerged between their results unless there is another factor which has also been varying without that variation being measured or allowed for. In fact, another field of research in recent years has indicated that air entrainment by such jets can vary significantly from one model arrangement to another depending on such factors as velocity, jet angle, internal turbulance, general boundary conditions etc.

Furthermore there is generally thought to be a considerable difference between the relative amounts of air entrained by model and prototype flows. This might relate to the apparent differences between model and prototype scour analysis results mentioned earlier. This is a particularly relevant point if one accepts the argument that entrained air aids hydraulic energy dissipation (see discussion by Mason (1985) and associated comments by Kenn and Novak) and perhaps, by inference, reduces scour depths.

There has also been one earlier, if fairly simple, study by Johnson (1967) where a set percentage of compressed air was injected onto a mobile bed along with a water jet. It was noted that scour decreased when air was included, compared to the scour achieved by the water jet acting alone.

It was decided to build a model in which the various parameters already identified could be varied in turn but with air also included as one of those parameters. The remaining Chapters describe how this was done and present the results achieved. These results are then examined in relation to model results by others and to known case histories of prototype scour.

Establishing the correct amounts of air to be introduced is clearly a fundamental part of the study. As this too is a field where research is still being actively carried out, Chapter 2 presents a state-of-the-art review into the entrainment of air by plunging water jets.

CHAPTER 2

AIR ENTRAINMENT BY FALLING JETS

2.1 Introduction

Ervine (1976) pointed out that there are basically two different types of air entrainment, the first when a high velocity flow gives rise to surface entrainment, the second where fast and slow moving bodies of water meet. In both cases the free water surface must be broken, that is the turbulent fluctuations of the flow must be strong enough to overcome surface tension. In the case of a free trajectory jet falling into a plunge pool the break up of the jet in the air, through the action of internal turbulent forces, will entrain some air while the undulating or broken surface of the jet entering the plunge pool will trap yet more. The same basic forces and mechanisms will apply to both a free jet entering a plunge pool or fast moving chute flow entering a stilling basin.

Many researchers have studied air entrainment and have considered a wide range of criteria such as Reynolds Number, Froude Number, Weber Number, velocity, turbulence intensity and boundary conditions. In civil engineering the research has been directed towards syphons stilling basins, dropshafts and oxygenation of water. In other fields entrainment of air has been studied by paint, detergent, food and molten glass manufacturers (Lin and Donnelly, 1966). Work on rectangular jets is limited and so to put what work has been done into perspective and to give a broad background to the matter, the following sections give a brief historic resumé, concentrating on recent experience.

2.2 The Hydraulic Jump

Perhaps the first attempts to quantify the degree of air entrainment for major civil engineering purposes was the work carried out by Kalinske and Robertson (1943). This concentrated on the hydraulic jump in closed conduits where the entrainment of air by the flow and its subsequent release can have very important design implications.

The formula they derived was:

$$\beta = 0.0066\ (Fr - 1)^{1.4}$$

where β = The volumetric ratio of air to water (Qa/Qw) in the flow

and Fr = The Froude Number of the incoming jet.

The results of this work were later verified by Haindl and Sotornik (1957) in another series of model tests at a much larger scale.

At a prototype scale, however, the U.S. Army Corps of Engineers (1952) found that the Kalinski and Robertson expression underestimated air entrainment as measured at some of their gated outlet works. They redefined the equation for prototype application as:

$$\beta = 0.04\ (Fr - 1)^{0.85}$$

By 1964, additional prototype data indicated that this too was an under-estimate, a better fit upper envelope being provided by:

$$= 0.03\ (Fr - 1)^{1.06}$$

Figure 2.1 shows the last two of the above expressions plotted against measured prototype data. It can be seen from this plot that although the last expression above represents the best upper limit, none of the expressions could be used to accurately predict air concentration for any given conditions suggesting that the basic form of the expression is an over simplification.

2.3 Free Trajectory Jets

2.3.1 Oyama et al (1954)

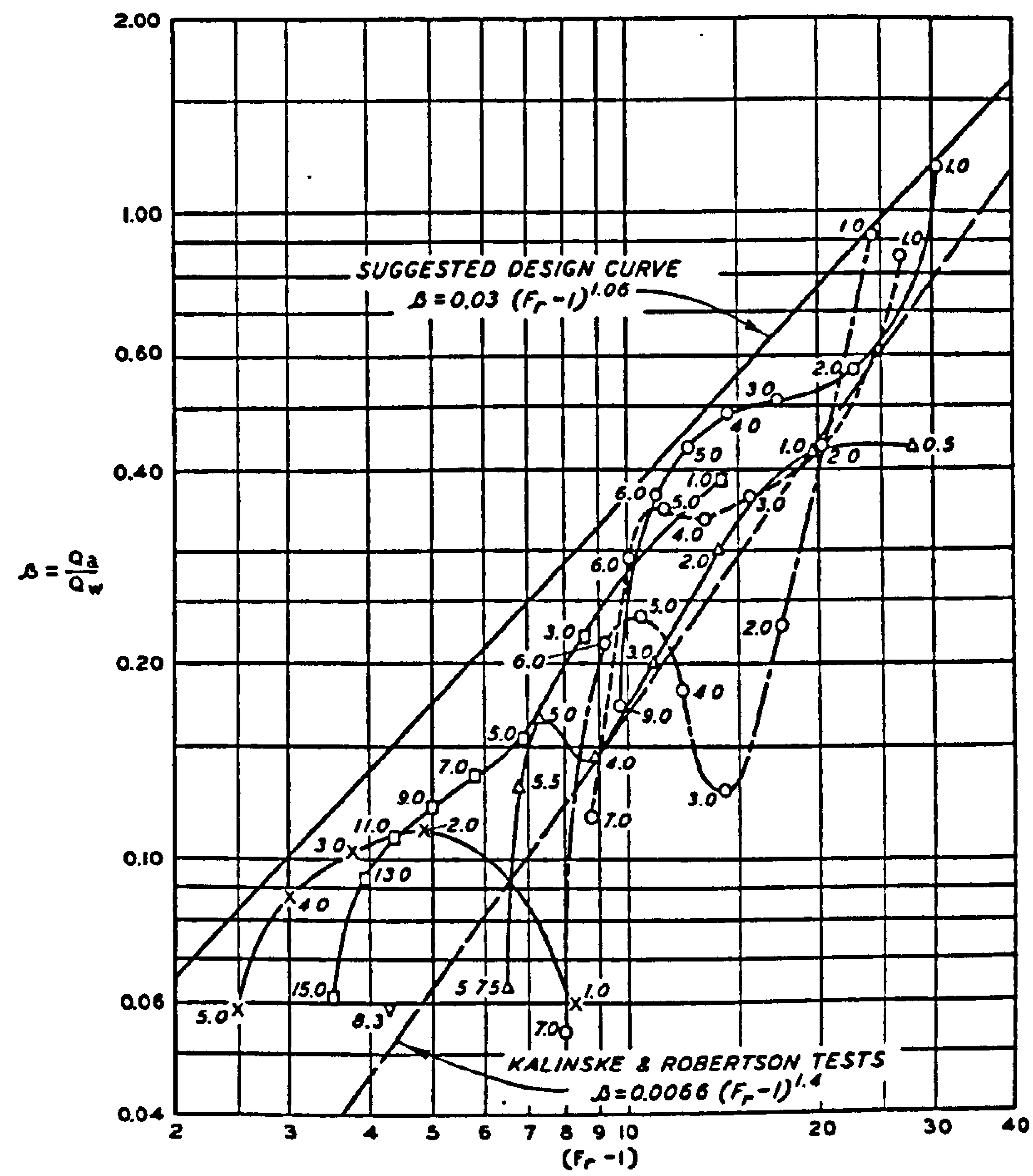
One of the earliest systematic studies of air entrainment to be frequently quoted, (Ervine et al 1980, Henderson et al 1970) was that by Oyama, Takashima and Idemura in 1954. For circular jets plunging into a liquid they found that*

$$= 0.75 \left(Re \right)^{1.33} \left(\frac{\sqrt{Wb}}{Re} \right)^{2.18} \left(\frac{Vn^2}{gLj} \right)^{-0.447} \left(\frac{Lj}{dn} \right)^{0.281}$$

where Re = Reynolds Number at the nozzle
We = Weber Number
Vn = Nozzle velocity
Lj = Jet length
dn = Nozzle diameter
g = Acceleration due to gravity

2.3.2 Lin and Donnelly (1966)

The work of Lin and Donnelly also featured circular jets and was carried out for the chemical industry. As a result they used a wide range of liquids such as water, mineral oil and different viscosity glycerols together with agents to modify surface tension effects.



NOTE : $F_r = V/\sqrt{gy}$ (FROUDE NUMBER)
V = WATER VELOCITY AT VENA CONTRACTA, FT/SEC
y = WATER DEPTH AT VENA CONTRACTA, FT
Q_a = AIR DEMAND, CFS
Q_w = WATER DISCHARGE, CFS

FIGURE 2.1 Air Demand at Regulated Outlet Works (U.S. Army Corps of Engineers, 1964).

They found that entrainment only occurs when the average jet velocity exceeds a certain critical value and that for laminar jets, where the velocity profile is fairly flat, this is defined when:

$$We = 10\left(Re\right)^{0.74}$$

See Figure 2.2.

This relationship means in turn that the minimum entrainment velocity, Ve, is given by:

$$Ve = \frac{6.22\ (\gamma)^{0.794}}{d^{0.206}\ \rho^{0.206}\ \mu^{0.587}}$$

where Ve = Minimum entrainment velocity (cm/sec)
γ = Surface tension of liquid (dynes/cm)
d = Jet diameter (mm)
ρ = Liquid density ($grms/cm^3$)
μ = Liquid viscosity (centipoise)

In all the above work by Lin and Donnelly the factors are calculated at the plunge point of the jet.

2.3.3 Horeni (1956)

Horeni is quoted by Ervine et al (1980) as having investigated the disintegration length of free rectangular jets being discharged horizontally. He obtained the expression for disintegration length (Ld):

$$Ld = 7.8\left(Re\right)^{0.319}$$

2.3.4 Henderson et al (1970)

Henderson et al worked with circular jets and visualised the turbulent jet with an undulating surface, as shown in Figure 2.3.

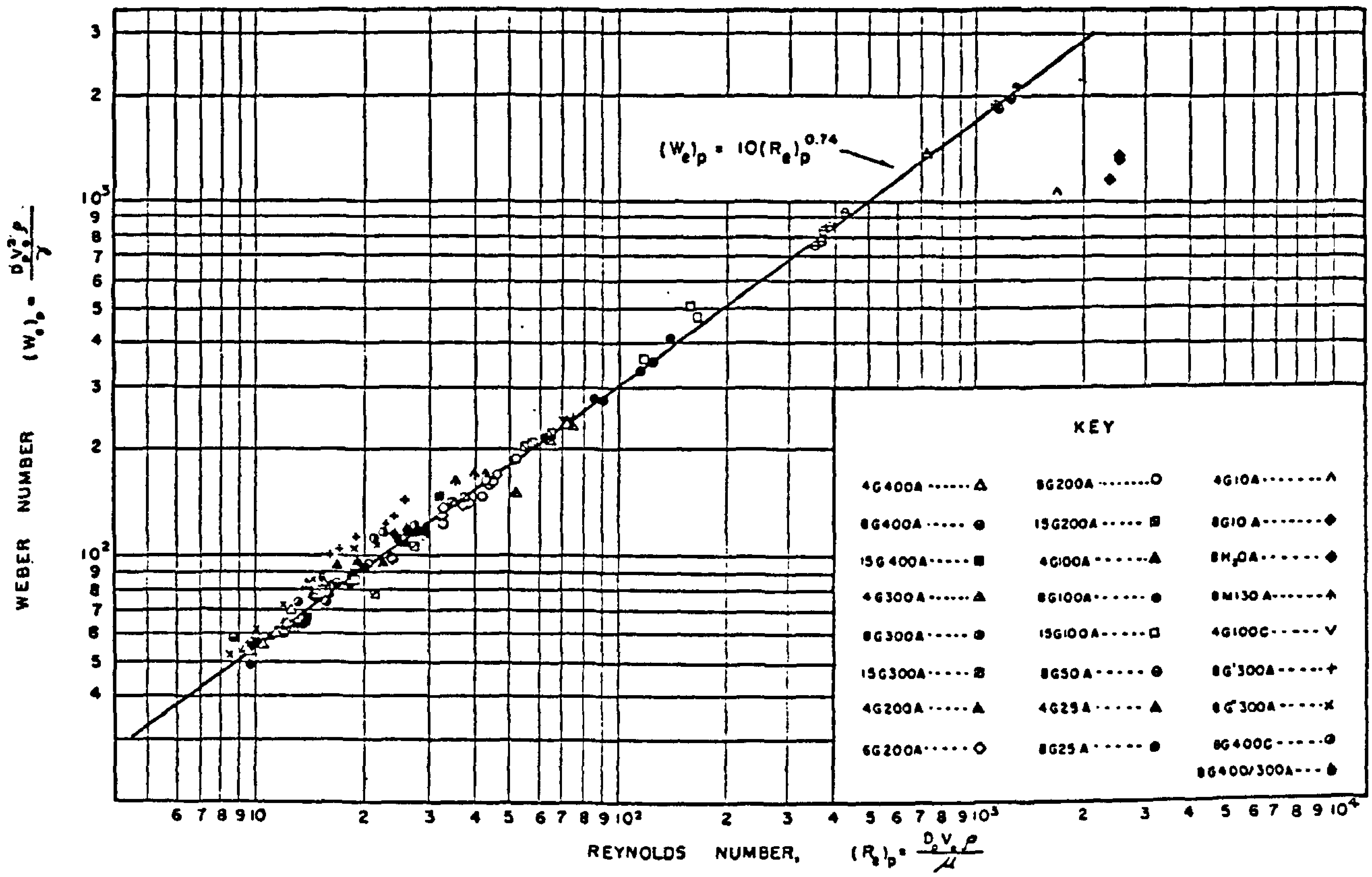


FIGURE 2.2 Minimum Entrainment Velocity Correlation (Lin & Donelly 1966).

They showed that the air entrained by a jet plunging into still water is given by:

$$\beta = \left(\frac{de}{dn} \right)^2 - 1$$

where de = The jet envelope at the point of impact determined by direct measurement of the plunging jet surface by photography

dn = Nozzle diameter

2.3.5 Baron (1971)

Baron is quoted by Ervine et al (1980) as having found that the disintegration length of a jet could be described by the Weber and Reynolds Numbers such that:

$$\frac{Ld}{d} = \frac{1.7 \quad We}{\left(Re \times 10^{-4} \right)^{0.625}}$$

2.3.6 Van de Sande and Smith (1973,1974 and 1975)

Van de Sande and Smith carried out extensive work on air entrainment by plunging jets in the early 1970's. Like most of their predecessors they concentrated their efforts on circular jets but extended their range to include high velocity jets.

They established (1973) that the diameter of the expanding turbulent jet can be defined by the expression:

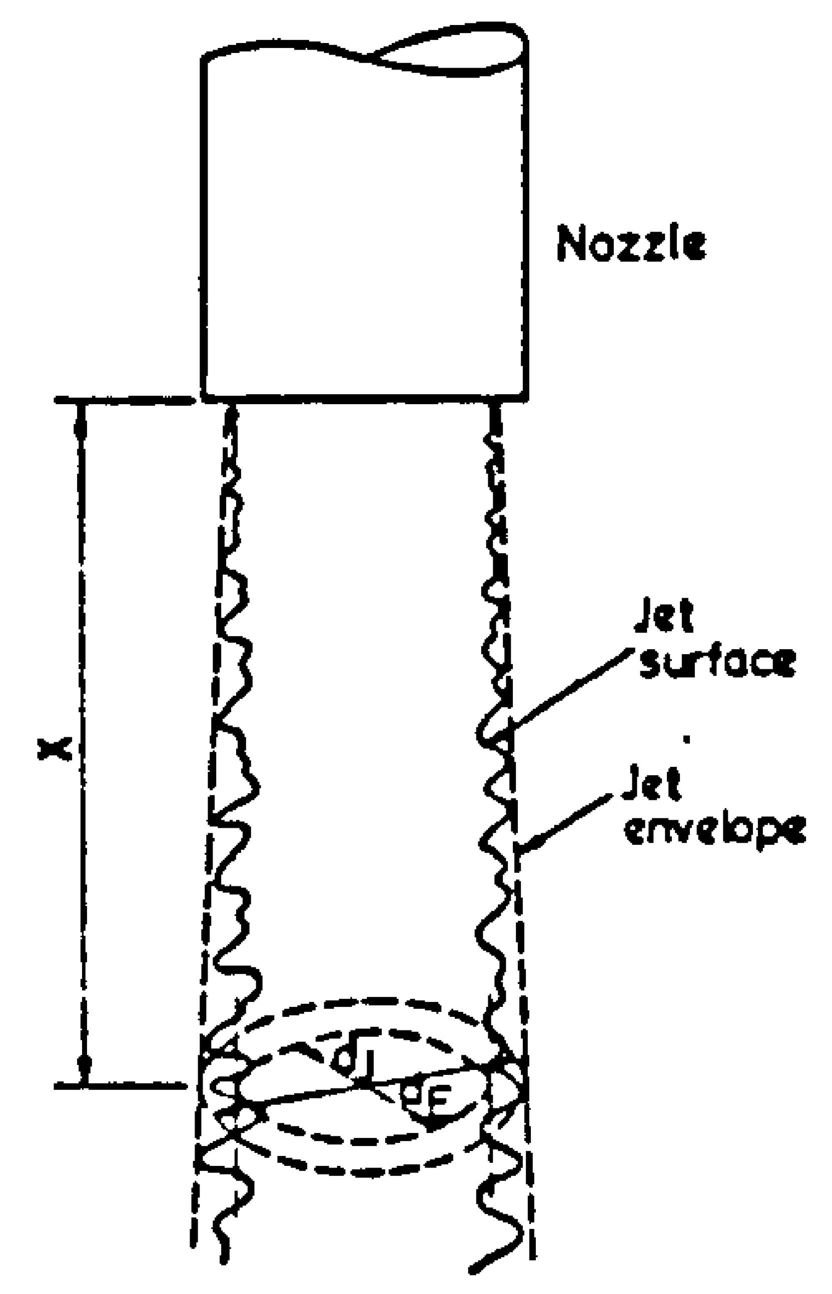


FIGURE 2.3 Jet Surface Roughness (Henderson et Al, 1970).

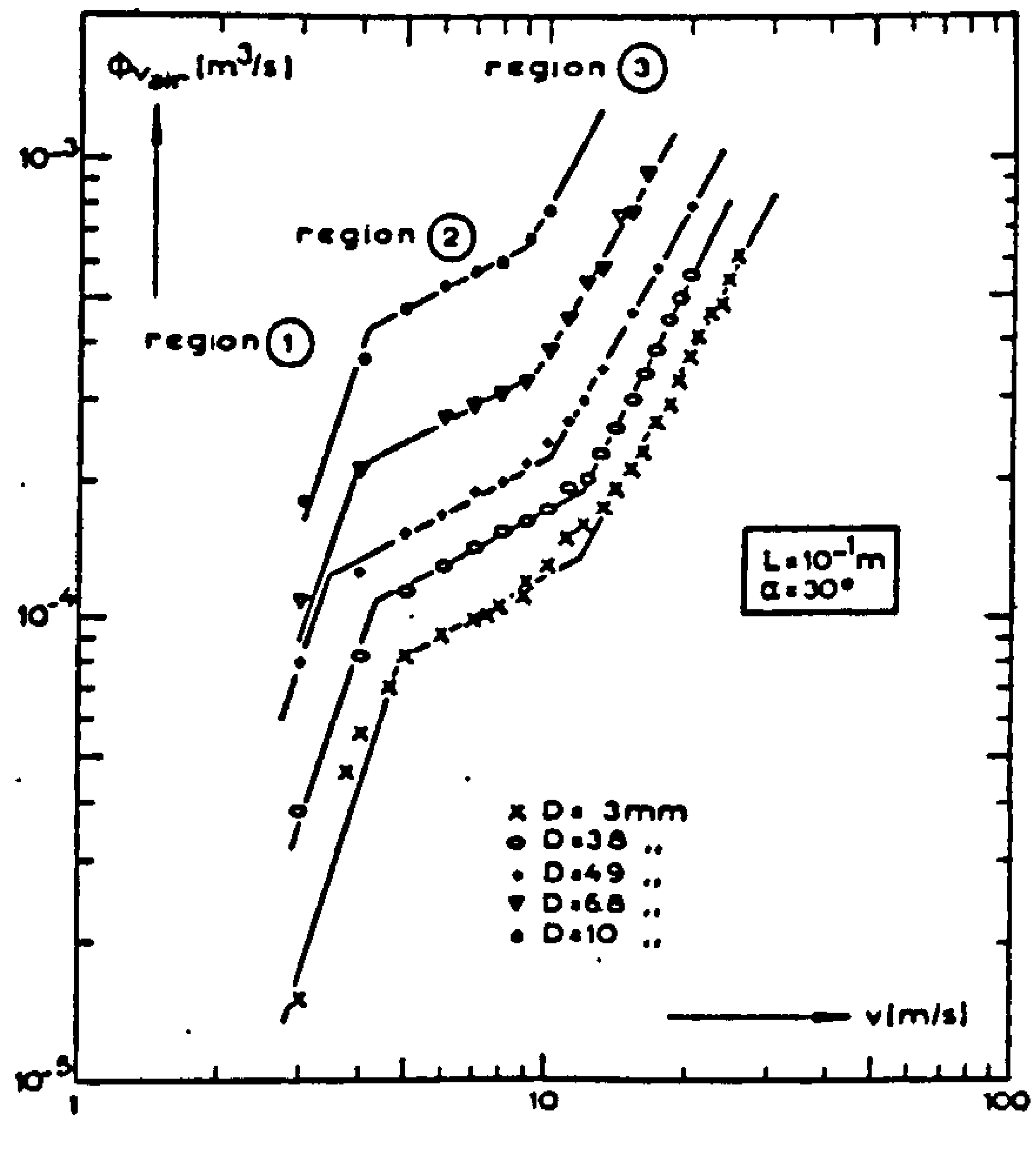


FIGURE 2.4 Air Volume Entrained as a function of jet Diameter and Velocity (Van de Sande & Smith, 1973).

$$\frac{d_j}{dn} = 0{,}085\ (We . Rel)^{0.167}$$

where dj = The long time averaged diameter of the jet at a distance L from the nozzle

dn = Nozzle diameter

We = Weber Number based on the density of air.

Rel = Reynolds Number based on jet length and diameter and density and viscosity of air.

As can be seen from the above, the work by Van de Sande and Smith (1973) depended on considering the development of the air boundary layer accompanying the jet. For their expressions to be valid they considered:

- the need for air friction with $We > 10$
- the need for a laminar air boundary with $Rel < 5 \times 10^5$

They considered that the total amount of air trapped in a plunge pool by a jet comes from two distinct mechanisms:

a. The air trapped within the surface undulations of the jet

$$Qat = \frac{\pi}{4} v \left(dj^2 - dn^2 \right)$$
$$= \frac{\pi}{4} v \, dn^2 \left(72.2 \times 10^{-4} We^{1/3} Rel^{1/3} - 1 \right)$$

b. The air dragged into the pool from the boundary layer of air accompanying the jet

$$Qab = \int_r^{\infty} V_{air}\ 2\pi r \ .dr$$

where $r = dj/2$

$V_{air} = v$

A theoretical graph is presented in order to enable Qab to be easily derived, from whence the total air entrained in the pool, Qa, is given by:

$$Qa = Qat + Qab$$

Van de Sande and Smith (1973) also note that a flat angle of jet introduces more air than a steep angle. They derived the expression:

$$Qa \propto (\sin \alpha)^{-0.25}$$

where α = the angle of jet to the horizontal

It is pointed out that this gives very little difference in entrainment volume between $\alpha = 60°$ and $\alpha = 90°$.

Perhaps one of Van de Sande and Smiths most notable findings at this time, however, was that there is a significant difference in relationship between the entrainment characteristics of high velocity and low velocity jets, see Figure 2.4 Below velocities of about 4.5 m/s the entrainment is irregular and very dependant on the form of the jet surface and the interaction between that and the plunge pool surface. At higher velocities the entrainment is more regular.

Assuming that:

$$Qa \propto v^x$$

For low velocity jets x = 2 to 3 whereas for high velocity jets x = 1.5 to 2.

In 1974 Van de Sande is reported by Bin (1984) to have produced a simpler formula for assessing air entrainment by vertical jets. This took the form:

$$\beta = 0.04 \ Fr^{0.56} \left(\frac{Lj}{dn}\right)^{0.4}$$

$\left(\text{Bin in fact quotes } Fr^{0.28} \text{ but where } Fr = \frac{V^2}{gdn}\right)$

This expression is examined by Bin against a range of data from others with promising results, See Figure 2.5.

In 1974 Van de Sande is also quoted by Bin (1984) as having produced the relationship*

$$Qa = 0.015 \left(dn^2 \ V_j^3 \ L_j^{0.5} \sin^{-1.5}\alpha\right)^{0.75}$$

This is essentially an energy expression implying that the volume of air entrained is proportional to the power of the jet. Again, Bin processes the equation using data from others with convincing results, See Figure 2.6. Note that the allowance for impact angle is at variance with Van de Sande's earlier expression of $(\sin \alpha)^{-0.25}$.

In 1975, Van de Sande and Smith considered bubble penetration depth as a function of jet parameters. They obtained the expression:

$$Dpb = 0.42 \ \frac{V_j^{1.33} d_j}{Qa^{0.25}}$$

where Dpb = Bubble penetration depth

2.3.7 Ervine (1976)

Ervine was one of the few researchers to concentrate his efforts on wide rectangular jets. He derived the expression:

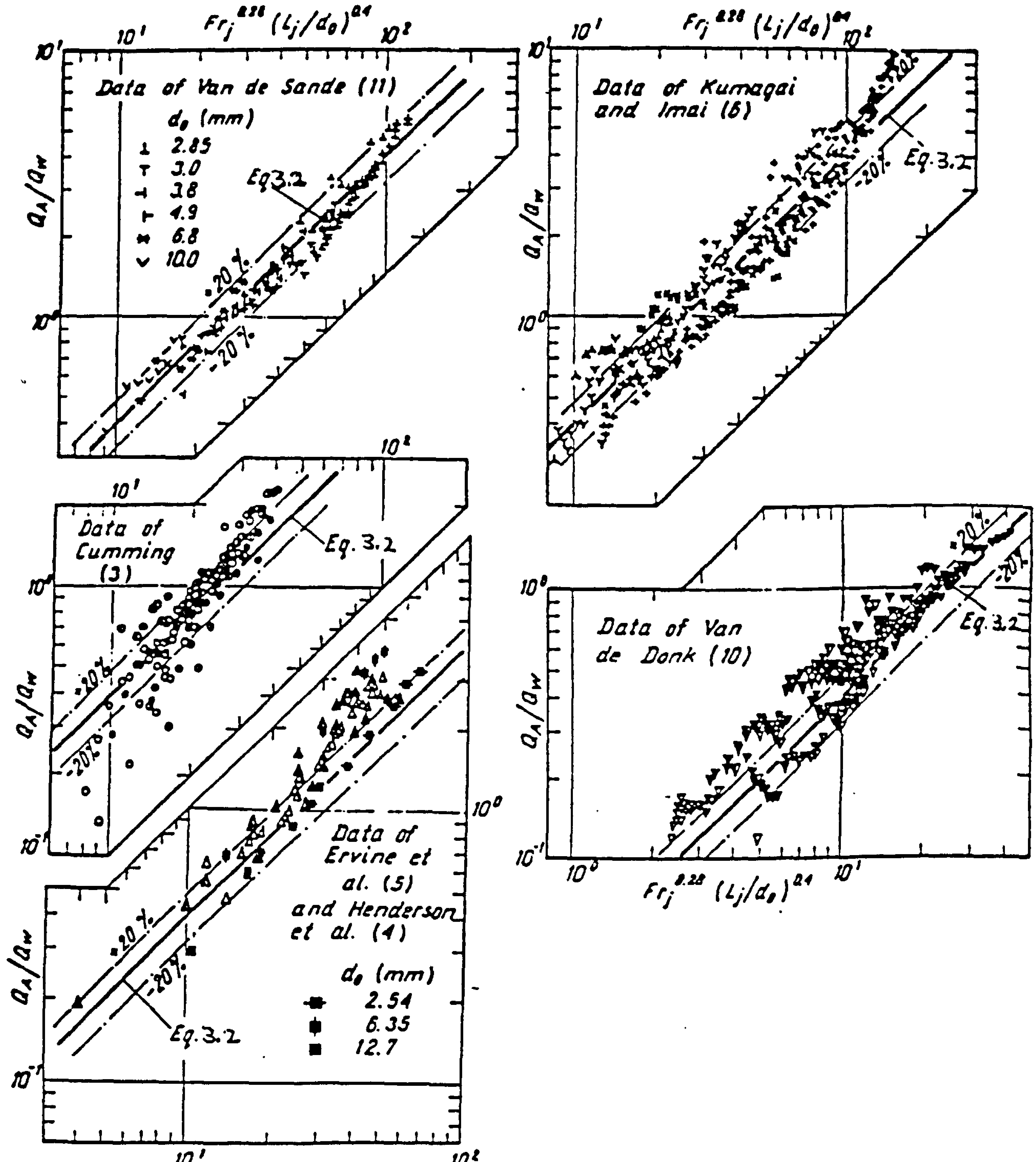


FIGURE 2.5 Air/Water Correlation (Bin, 1984).

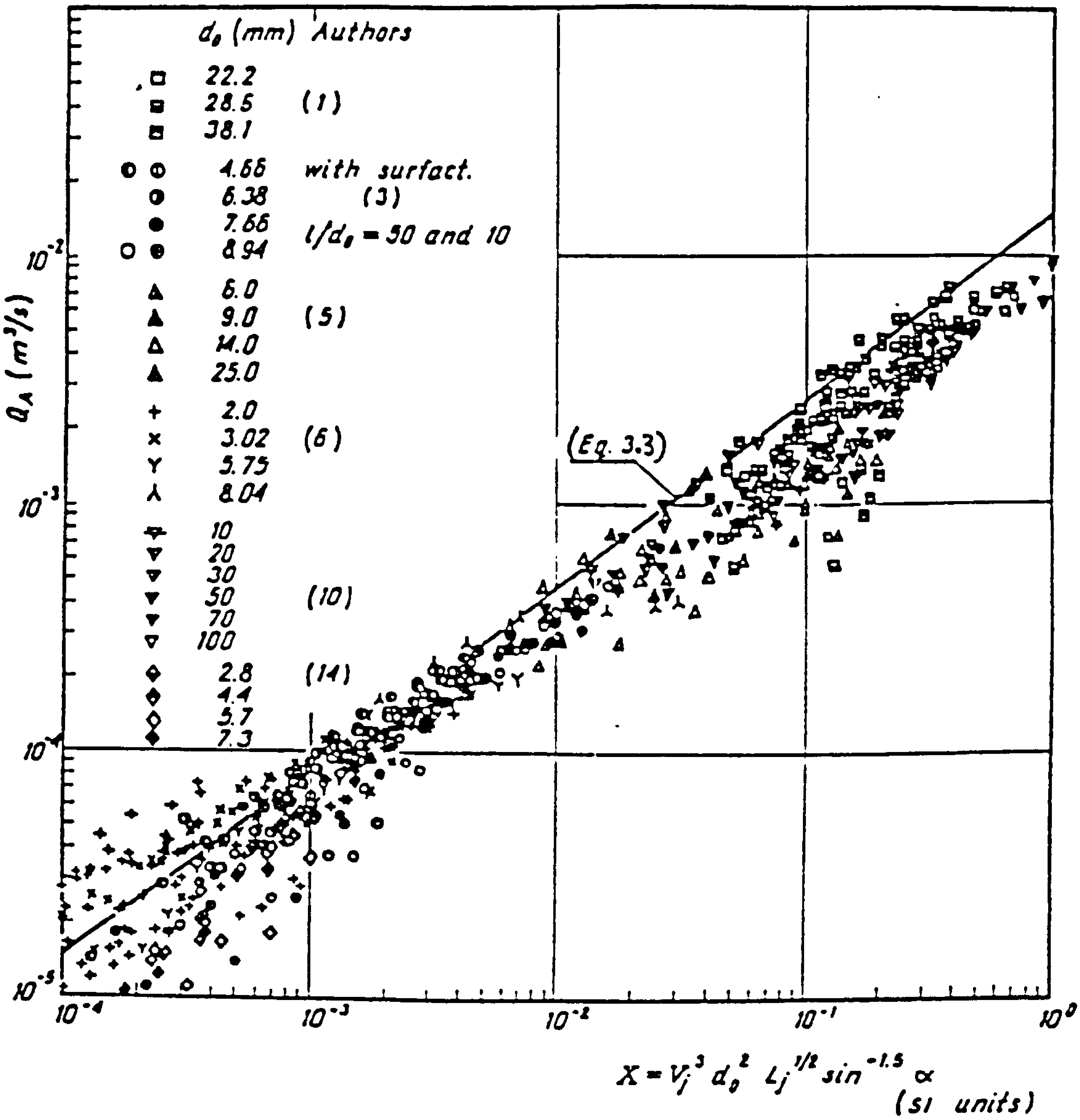


FIGURE 2.6 Air Flow Correlation (Bin, 1984).

$$\beta = 0.26 \left(\frac{b}{p}\right)\left(\frac{Hj}{t}\right)^{0.446} \left(1 - \frac{Ve}{V}\right)$$

where b = jet breadth or width
p = jet perimeter in contact with air
t = jet thickness
Hj = vertical fall height of jet
ve = minimum velocity of jet to entrain air (1.1 m/s)
v = jet velocity at impact.

It can be seen that for a wide jet b = approx. p/2, hence:

$$\beta = 0.13 \left(\frac{Hj}{t}\right)^{0.446} \left(1 - \frac{Ve}{v}\right)$$

See also Figure 2.7

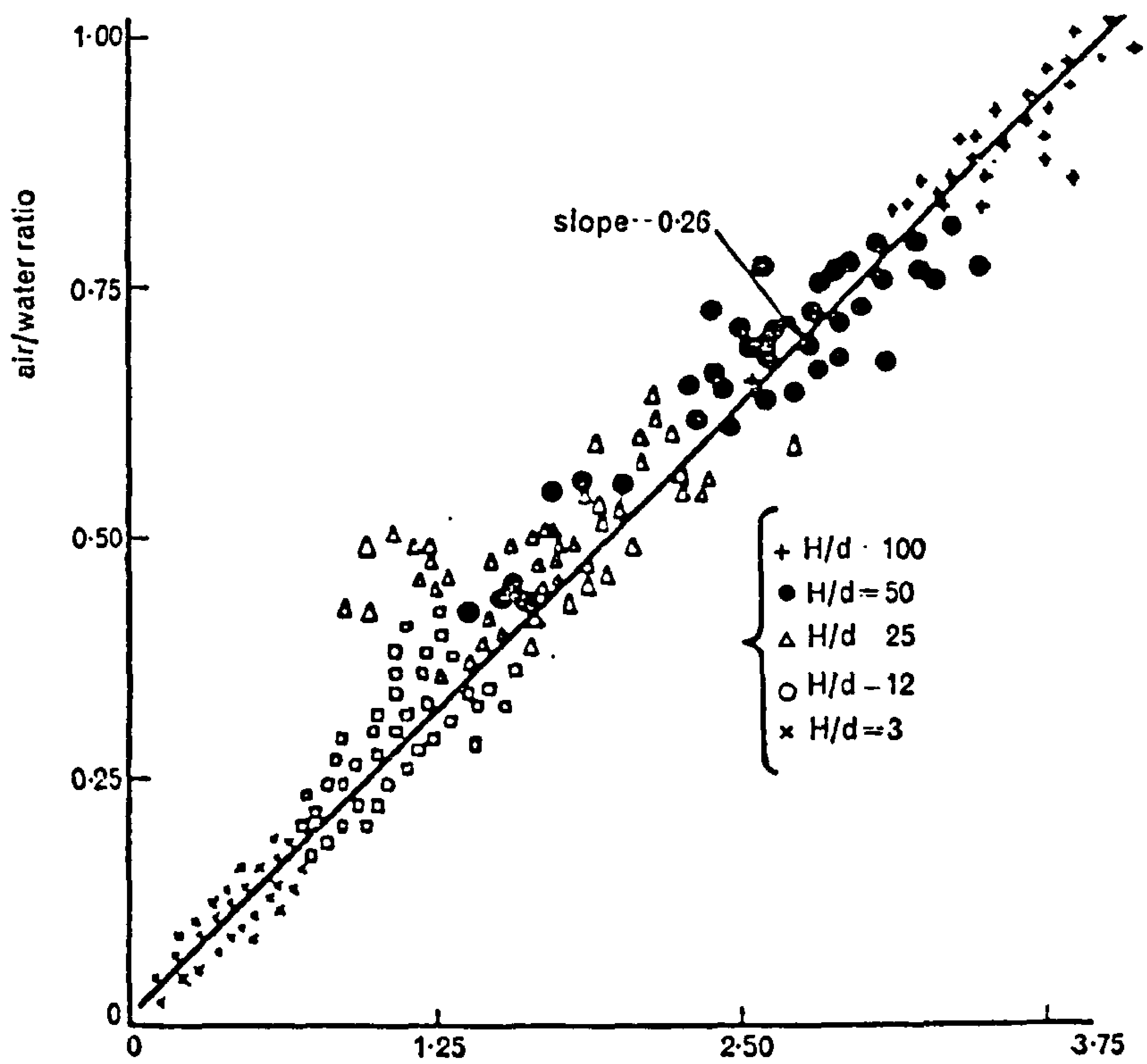
2.3.8 McKeogh and Elsawy (1980)

McKeogh and Elsawy argued that the air entrainment characteristics of a jet will be a function of the surface undulations and that both these and the disintegration length of the jet will in turn be a function of the turbulence intensity of the jet at the point of emission.

The turbulence intensity level is defined as:

$$ti = \frac{\sqrt{\overline{Vi^2}}}{V} \times 100\%$$

where Vi = instantaneous velocity fluctuation
v = jet velocity at any point.



Correlation of experimental results, after varying the nappe velocity V, *nappe thickness* d, *depth of fall* H *and nappe width* b. *The horizontal axis represents* $(b/p)(H/d)^{-}(1-V_o/V)$

FIGURE 2.7 Air/Water Ratio Correlation for Wide Rectangular Jets (Ervine, 1976).

The work was carried out with circular jets and it was found that disintegration length, Ld, was very dependant on turbulence intensity as was minimum entrainment velocity, ve, and volume of air entrained, Va.

For Smooth Jets:

$$ti = 1\%$$
$$ve = 2.8 \text{ m/s}$$
$$Ld = 38\ Qw^{0.369}$$
$$Va = 0.9\ Vad \left(\frac{Hj - Hje}{Ld} \right)^{0.87} + Vae$$

where Hj = Vertical fall height of jet
Hje = Fall height corresponding to ve
Vad = Air volume entrained when Hj = Ld
Vae = Air volume correspnding to ve

For highly turbulent jets:

$$ti = 5\%$$
$$ve = 0.8 \text{ m/s}$$
$$Ld = 4.6\ Qw^{0.20}$$
$$Va = 0.88\ Vad \left(\frac{Hi}{Ld} \right)^{0.85} + Vae$$

McKeogh and Elsawy also examined the effect of restricted penetration depth on the volume of air retained in the plunge pool.

2.3.9 Ervine et al (1980)

Ervine, McKeogh and Elsawy took the matter of turbulence intensity still further in 1980 by examining it as a function of the undulating surface disturbance of the jet. For a jet of radius, r, at impact and a mean surface disturbance thickness, s, they showed that:

$$\beta = 14 \left(\left(\frac{S}{r} \right)^2 + 2 \left(\frac{S}{r} \right) - 0.1 \right)^{0.6}$$

This is stated as being valid for

- jet velocities up to 6 m/s
- nozzle diameters from 6 to 25 mm
- turbulence intensities of 0.3 to 8%
- heights of fall up to Ld.

They also tabulate values of minimum entrainment velocity against turbulence intensity as follows:

ti (%)	Ve (m/s)
0.3	3.6
1.0	2.5
3.0	1.0
8.0	0.8

2.3.10 Rogola (1981)

Like Ervine (1976) Rogola worked with rectangular jets. He carried out two dimensional tests on the low trajectory nappes falling from models of tilting flap gates. He obtained the expression:

$$= 0.78 \times 10^{-9} \, Fr^{1.51} Re^{1.1}$$

There were, however, various aspects of the study which might make general application difficult:

a. Whereas the Froude Number is based on the jet thickness at impact, the Reynolds Number is based on the energy head over the weir. This could vary according to the discharge coefficient of the gate (which will vary in any case for any given gate) independantly of impact thickness.

b. Air demand was measured for the lower surface of the nappe only and did not therefore represent total entrainment.

c. The impact angle of the jet was low and presumably varied. This would give varying results for air entrainment (see results by Van de Sande) which have not been allowed for by Rogola.

2.3.11 Van de Donk (1981)

According to Bin (1984) Van de Donk carried out work on circular jets and neglected velocity to obtain the expression:

$$= 0.09 \left(\frac{Lj}{dn}\right)^{0.65}$$

2.3.12 Bin (1984)

Bin carried out a brief survey of plunging jet entrainment, which concentrated on the work of Van de Sande. He also summarised work on estimating the penetration depth of bubbles, Dpb, again proposing a relationship developed by Van de Sande (1974):

$$Dpb = 2.4 \; Vn^{0.66} \; dn^{0.66} \quad (\text{when } Vndn \geqslant 0.01)$$
$$\text{and } Dpb = 61 \; Vo^{1.362} \; dn^{1.362} \quad (\text{when } Vndn < 0.01)$$

2.4 Conclusions

It is clear from the summary in Section 2.3 above that, at the time of writing, there is still room for speculation about both the quantities of air likely to be entrained by falling jets and the parameters from which the degree of entrainment can be calculated. As Ervine (1985) phases it "A lot more research is required on plunging jets especially at larger scales and velocities"

In spite of the variation, some consistancies do appear, consider the following expressions:

$$\beta = 0.04 \; Fr^{0.56} \left(\frac{Lj}{dn} \right)^{0.4} \qquad \text{Van de Sande (1974)}$$

$$\beta = 0.13 \left(1 - \frac{Ve}{v} \right) \left(\frac{Hj}{t} \right)^{0.446} \qquad \text{Ervine (1976)}$$

$$\beta = 0.09 \left(\frac{Lj}{dn} \right) 0.65 \qquad \text{Van de Donk (1981)}$$

In discussions with Ervine (1986) it was suggested to the writer that the air entrainment of plunging jets could be generally and approximately assumed to take the form:

$$\beta = K \left(\frac{H}{d} \right)^{0.5} \qquad \text{for circular jets}$$

and $$\beta = K \left(\frac{H}{t} \right)^{0.5} \qquad \text{for rectangular jets.}$$

Furthermore that K depended on the turbulence intensity and varied from 0,2 to 0,4 for circular jets and 0,1 to 0,2 for rectangular jets. Ervine has studied in depth all forms of air entrainment and appears to be the only Author to have investigated the overall entrainment of steep rectangular jets. It was therefore decided that all work in connection with those studies on scour under such jets would adopt Ervine's 1976 formula for assessing probable equivalent free fall air entrainment. That is:

$$\beta = 0.13 \left(1 - \frac{Ve}{v} \right) \left(\frac{Hj}{t} \right)^{0.446}$$

It is accepted that absolute accuracy may not be possible but it is expected that the trends in variation of air entrainment with v, Hj and t will be reliably reproduced.

CHAPTER 3

THE SCOUR TEST APPARATUS

3.1 Introduction and General Principles

Following from the discussions in Section 1.5 it is clear that the primary purpose of the apparatus was to be able to individually vary parameters such as unit flow q, head drop H and the amounts of entrained air in a controlled manner, in order to establish their effects on scour depth. It was decided to build an apparatus which incorporated as many facilities as reasonably possible so as to enable the direction of testing to be changed or expanded should the need be indicated by results.

One fundamental decision made at the start was that in order to accurately gauge the amounts of air being added to the jet, the main jet should be introduced below tailwater level, thus excluding natural boundary entrainment at the water surface. After some discussions with the City University Laboratory Staff and taking account of their preferred techniques and the available materials, the writer produced basic drawings for the apparatus which are included here as figures 3.1 and 3.2. In fact, in the form presented they also include some of the modifications subsequently made which are described further in Section 3.3 below.

In developing the concept for the apparatus the following aspects were considered:

* The need to vary the head, H, over a reasonable range, say up to 2 m.
* The need to correspondingly adjust unit flow, q, to predetermined values.
* The ability to introduce predetermined amounts of entrained air into the jet and also to exclude air.

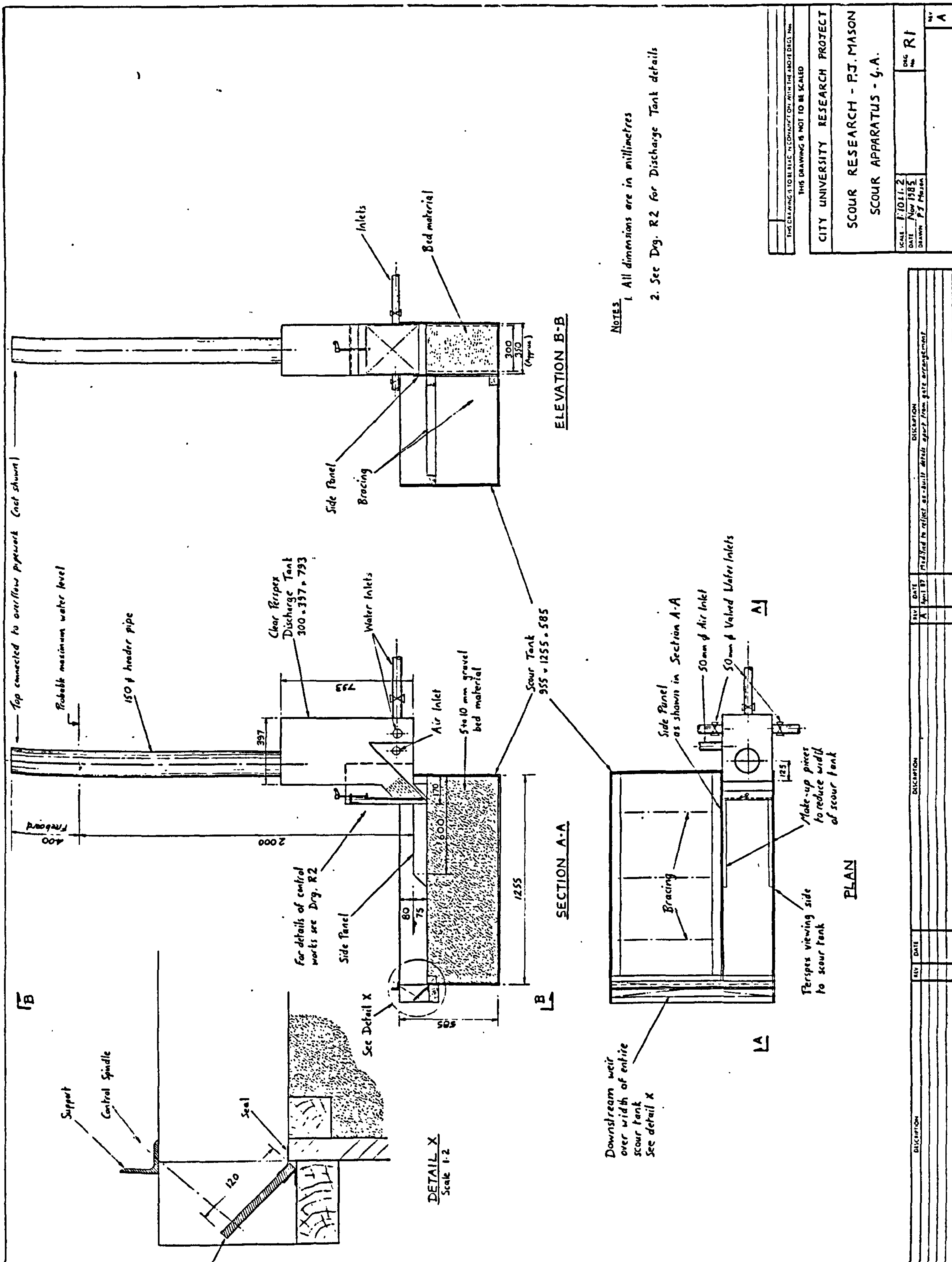


FIGURE 3.1

Scour Apparatus

General Arrangement.

FIGURE 3.2 Discharge Tank Details.

* The ability to vary the angle of the jet.
* The option of carrying out 2 dimensional or 3 dimensional scour tests.
* The ability to view the scour process from the side, via a clear perspex or acrylic panel.
* The ability to develop fairly deep scours, say up to 0.5 m.
* The ability to vary or modify tailwater depth.
* The option of changing bed materials.

In the event and in the interest of expediency, a fixed jet angle of 45° was adopted. This reflected values commonly found in prototypes. Nor were the options of varying the bed material or carrying out 3 dimensional testing taken up.

The apparatus as constructed is shown on Figures 3.3 to 3.6 and individual aspects of it and its planned mode of operation are described in Section 3.2 below.

3.2 Details of the Apparatus

The apparatus comprised basically of:

* A discharge tank in 10 mm acrylic, which incorporated a riser or header column, an adjustable discharge gate and air and water supplies.
* A scour tank in 20 mm plywood but with a braced, 10 mm clear viewing panel on one side and an adjustable end weir. This tank housed the mobile bed.
* A collecting, or sump tank in sheet metal, which was also used initially for flow calibration purposes.
* Water supplies from the laboratory ring main.
* A high volume, low pressure, fan driven air supply to the discharge tank via a calibrated KDG, Rotameter type flowmeter.

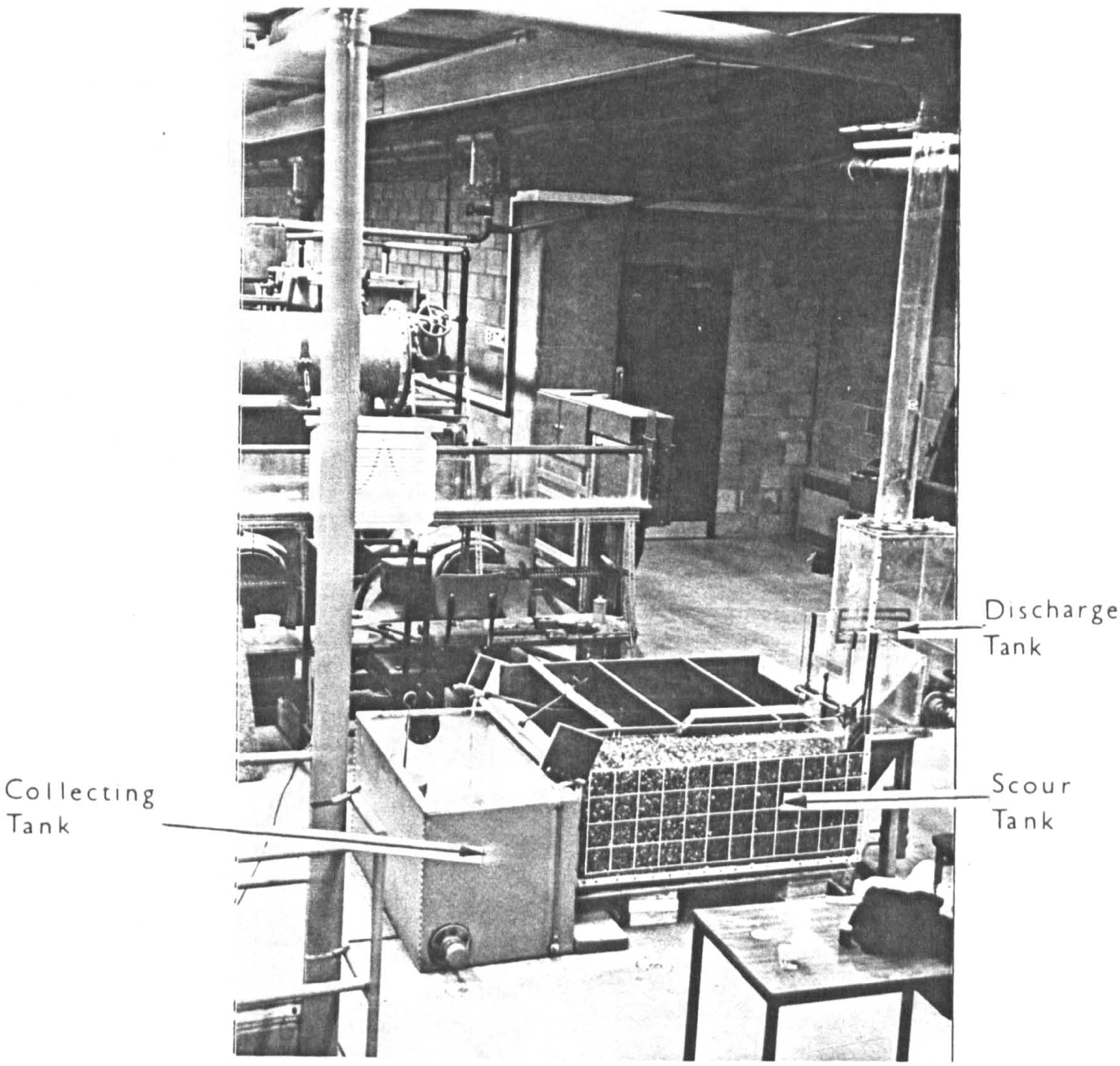


FIGURE 3.3 Scour Apparatus as Constructed - 1.

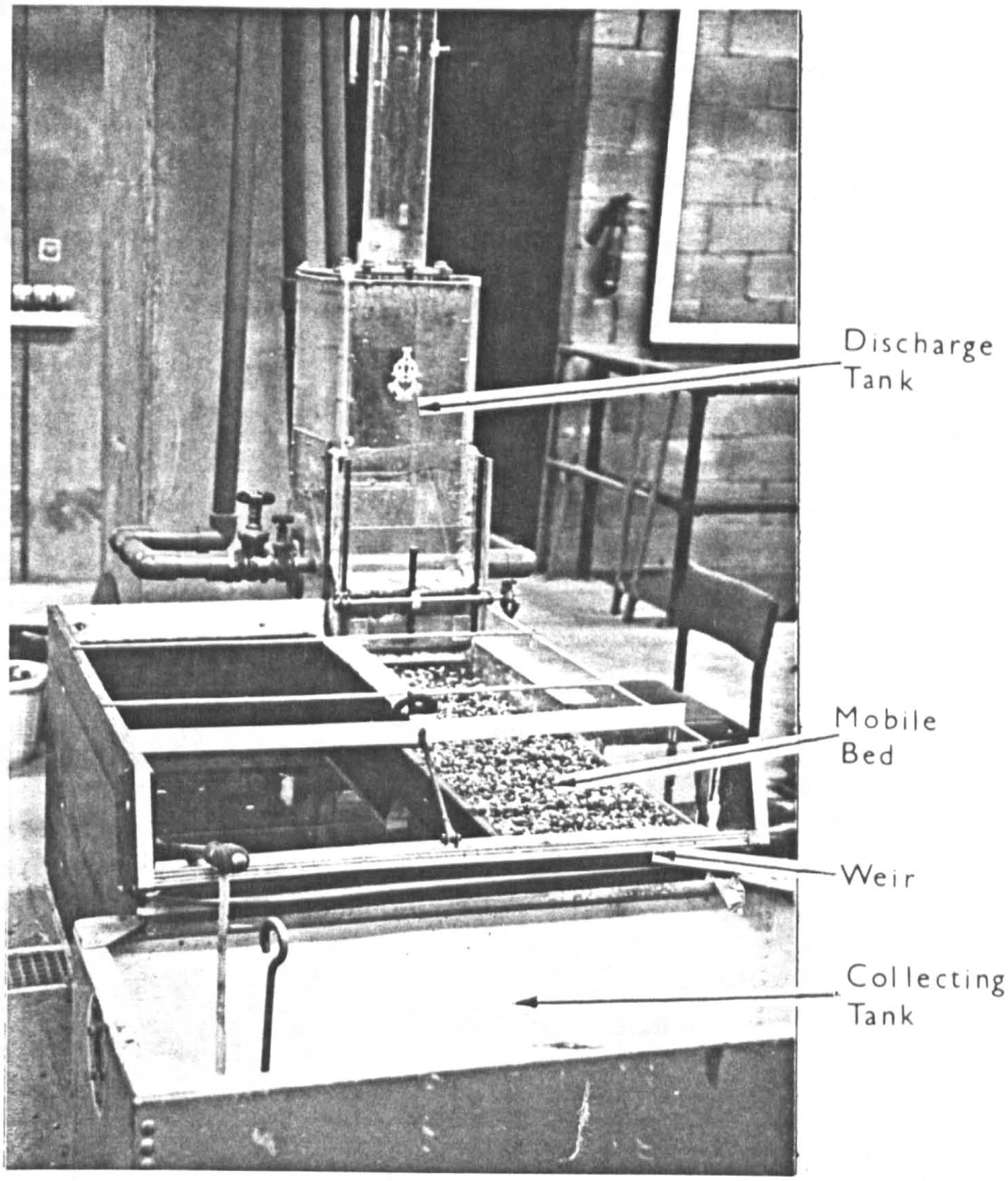


FIGURE 3.4 Scour Apparatus as Constructed - 2.

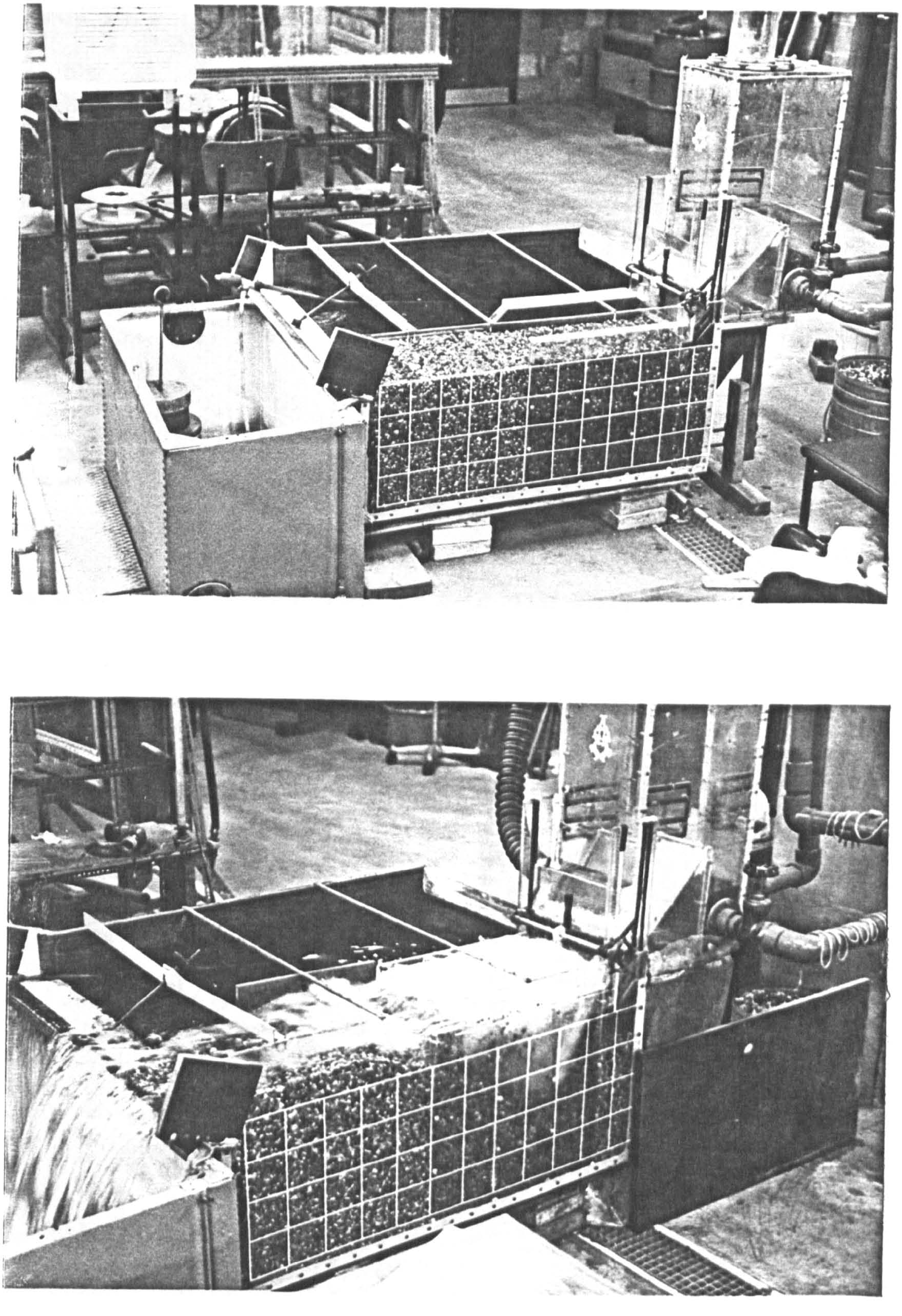
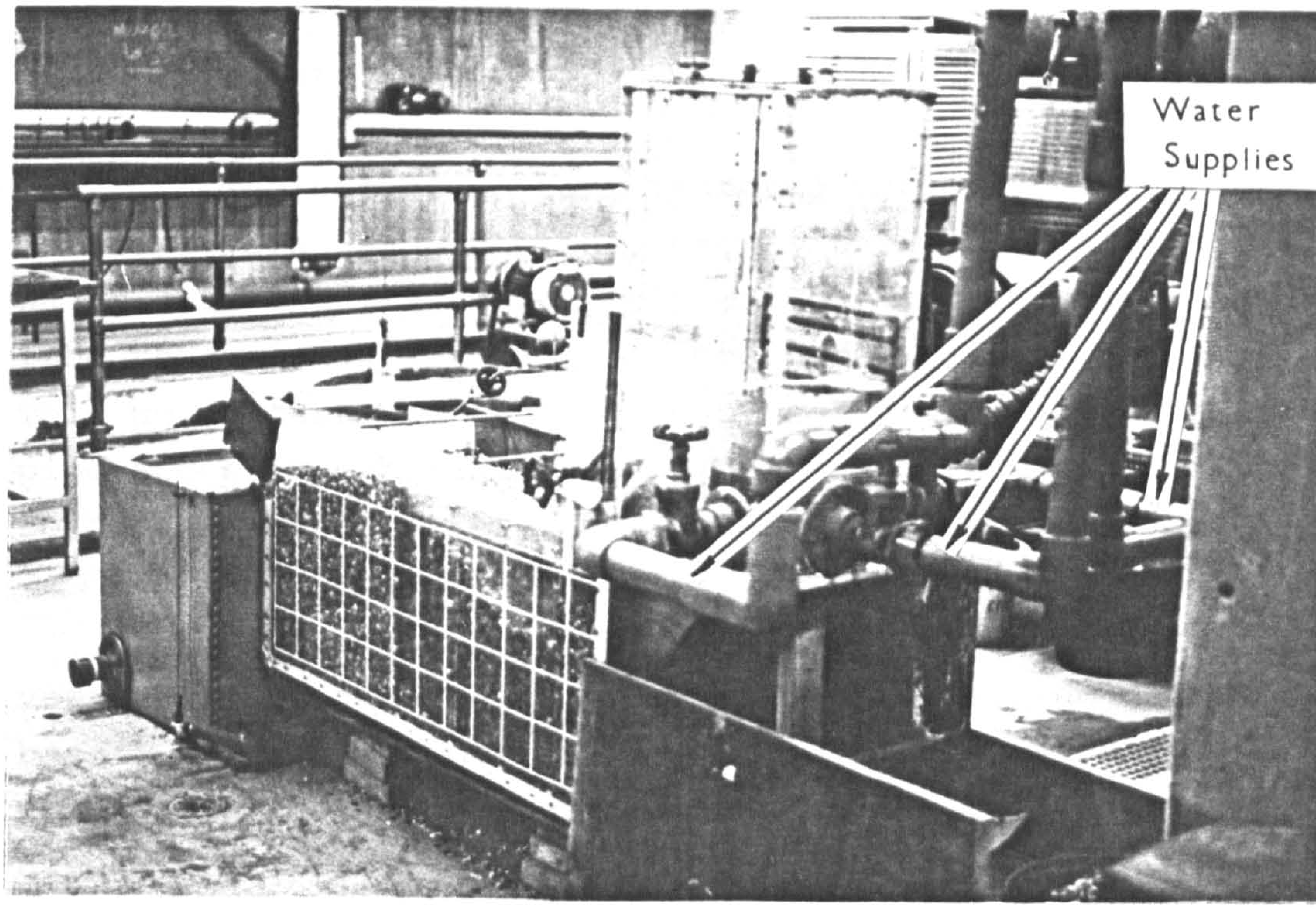


FIGURE 3.5 Scour Apparatus as Constructed - 3.



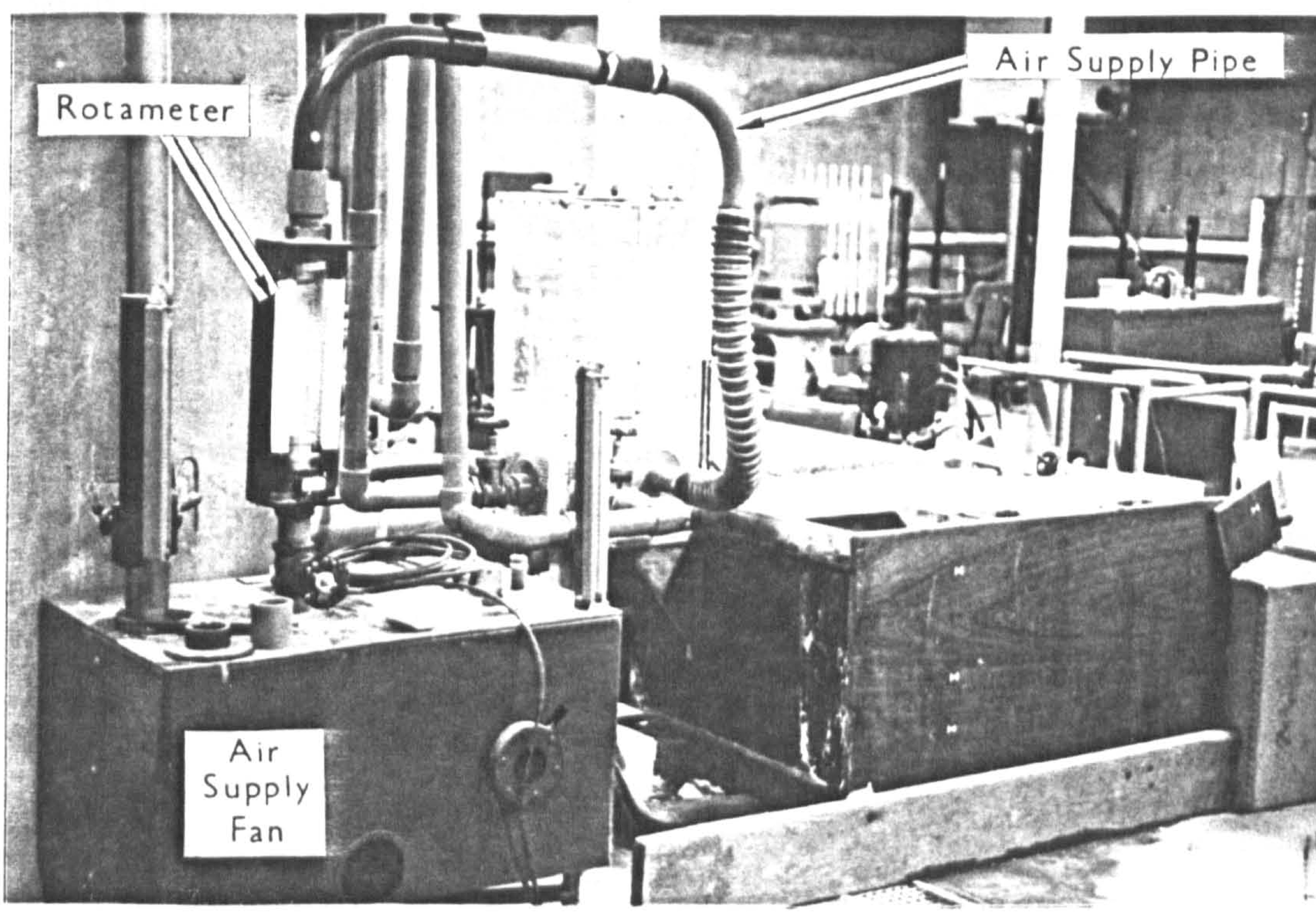


FIGURE 3.6 Scour Apparatus as Constructed - 4.

3.2.1 Discharge Tank

The discharge tank featured three, 50 mm diameter incoming water supply pipes, each with its own gate valve. Water entering via these pipes was deflected upwards, away from the main outlet area, to the upper part of the tank. This upper part was surmounted by a 150 mm diameter riser pipe and both tank and riser pipe were calibrated vertically so that internal water levels could be measured.

Discharges from the tank were controlled by a vertical lift gate which sealed against a 45° degree sloping base. The lip was originally fitted with a matching 45° guide plate to ensure that parallel 45° flows were discharged at all gate openings. This had to be modified later, see 3.3 below. It was originally envisaged that lifting the gate would be via a vertically aligned spindle mechanism, much as shown on Figures 3.1 and 3.2. In fact the as-constructed detail, see Figures 3.3 to 3.6, featured a horizontal spindle with a centre cog acting directly on a metal, toothed bar sited vertically on the outside of the gate. This arrangement had the advantage of bracing the centre of the gate.

At any given gate opening a required head could be achieved by adjusting the inlet valves. At any given head within the system a required outflow could be achieved by adjusting the outlet gate and inlet valves together. Pre-determined values could be set very rapidly by pre-calibrating the system and this is described in 3.4 below.

The system for supplying air is described in 3.2.5 below. Air entered into a sealed triangular chamber at the base of the discharge tank. It entered via an embedded length of pipe which was slotted longitudinally to give an even distribution of air. It exited from the chamber through a fixed 12 mm gap immediately underneath the water outlet. It was reasoned by the writer when adopting this arrangement that the expelled air would have to rise and would hence become entrained in the water jet issuing immediately above. In the event the system worked very effectively. Introduction of the air into the jet was deliberately made to take place downstream of the control gate so that the gate discharge arrangements could be pre-calibrated and then operated independently of air provisions.

3.2.2 Scour Tank

The scour tank housed the mobile bed, see 3.2.6 below, and featured a clear viewing panel on one side. This panel was marked with white strips at 10 cm centres vertically and horizontally to facilitate subsequent measurements.

A partition was sited in the tank to form a channel which matched the width of discharge tank and hence enable 2 dimensional flow and scour conditions to be created, see also Section 3.3 on modifications. The height of the partition was lowered towards the downstream end of the tank to allow the flow to spread laterally and hence prevent excessive tailwaters at high flows. Tailwater levels were in fact controlled by an adjustable weir sited downstream as shown in Figure 3.1.

3.2.3 Collecting Tank

Water passing over the weir at the end of the scour tank fell into a sump or collecting tank. The outlet from this was in turn an approximately 200 mm dia, plastic flanged hole in the base of the tank which discharged into the main laboratory collecting sump beneath the floor. Water levels in the tank were indicated on an external glass tube.

During initial calibration of the apparatus the flanged hole could be covered as required by a lever-operated, blank plate. Rises in water level in the tank could then be viewed in the glass tube and timed. Subsequently the plate and lever were replaced by a circular screen which allowed water to exit but trapped any mobile bed material flushed out from the scour tank. The plan area of the collecting tank was approximately 120 cm x 60 cm.

3.2.4 Water Supply

The water used in the tests was taken from the high head ring main which served the whole hydraulic laboratory. Each tapping point from the main had three 50 mm diameter outlets and three such outlets were used to supply the discharge tank. This arrangement was able to supply flows of up to approximately 18 litres/sec.

3.2.5 Air Supply

Air was supplied by a high volume, low pressure fan. This choice was deliberate as clearly the flows of air had by calculation to be of the same order as the water flows while the writer did not want to inject air under high pressure in case this added energy to the entrained jet thus distorting any comparative results. Instead, as mentioned in 3.2.1 above, the air was in effect made available for the waterjet to entrain.

The fan supplied air through a vertical pipe. A valve was added to the pipe to enable adjustment and a Rotameter flowmeter was mounted above that. After the Rotameter, the air passed through a 50 mm diameter supply pipe to the discharge tank. The flowmeter used was a size 65 Rotameter. This, coupled with a stainless steel float, was already part of the laboratory's equipment for measuring water flow. A new aluminium float was obtained, together with appropriate calibration curves and this enabled it to be used for measuring air flows of between 3.5 and 35 litres/sec at N.T.P.

3.2.6 Mobile Bed Material

It was established by the review in the previous M.Phil. study that particle sizes less than 3 mm should generally not be used in this type of modelling. Such sizes can be susceptible to Reynolds Law, viscous effects whereas plunge pool scour is essentially a fully turbulent, Froude Law process. It has also been established by workers such as Doddiah et al (1953) that the grading of bed material can greatly affect results. In fact the earlier M.Phil. study highlighted a divergence of opinion concerning whether the d_{50}, d_{85} or d_{90} size should be taken as the characteristic particle size when considering this form of scour.

In order to allow for both these factors a close graded 5 to 10 mm crushed gravel aggregate was used for all tests. This was available from the University's Concrete Laboratory aggregate bins and represented, in effect, as near a single sized material as reasonably possible. Quantities of the aggregate were taken for testing at the materials laboratories of Sir Alexander Gibb & Partners and the resulting grading curve is shown on figure 3.7. The material was also found to have a voids ratio of exactly 40%.

3.3 Initial Operation and Modifications

The apparatus generally behaved well when tested. It was found to be relatively easy to ensure stable head conditions, within fluctuations of say $\pm$ 1 cm. Operating all three inlet valves fairly equally also seemed to ensure fairly even flow conditions within the discharge tank. Two early problems which did arise concerned the vertical lift gate and the width of the scour channel.

During the course of initial trials the vertical lift gate closed suddenly and without warning. Inflow then transferred to the 150 mm diameter riser pipe, overflowing

PARTICLE SIZE DISTRIBUTION

GRADING CURVES

SAMPLE No:

SAMPLING DETAILS: Date

Location

Weight 5000 gms

Remarks

TEST DETAILS: Date 15th Jan 1987

~~Wet~~ / dry sieved

Dispersing agent

H_2O_2 .... Acid treatment

Other

OTHER TEST RESULTS:

LL = ... PL = ... PI =

Natural moisture content .... %

Specific gravity

Other

PROJECT:

FIGURE 3.7 Grading Curve of Bed Material.

SIR ALEXANDER GIBB & PARTNERS
Consulting Engineers
Earley House
427 London Road
Earley, Reading, UK

Job No

Fig No.

generally over the whole apparatus. The problem was due to the 45° guide plate which was attached to the lip of the gate, see details given in 3.2.1 above. Under discharge conditions the reduction in pressure beneath the plate due to the velocity head caused the higher, static head pressure above to force the gate down. The guide plate was removed and replaced by a block of metal foil honeycomb, not attached to the gate leaf but wedged in position immediately upstream of it, see Figure 3.2. This had the same, intended effect of ensuring 45° parallel flows at all gate openings. After this modification no more problems occurred with unforeseen gate movements and the leaf remained exactly where positioned throughout all subsequent tests. Even so, to guard against mal-operation of the inlet valves or other, unforeseen, circumstances an overflow pipe was fitted to the top of the riser to enable excess heads to discharge safely and remotely.

The scour channel was initially made slightly wider than the gate width of 300 mm in order to accommodate the thickness of the various discharge tank side plates. Although this was only in the order of 20 mm per side, this was sufficient to allow lateral return currents to develop. These in turn caused the jet to concentrate towards the centre of the channel. the problem was solved by adding side plates to the scour channel to reduce the width of that to 300 mm to match the gate width. These are indicated on Figure 3.1. The side plate on the clear panel side of the channel was also made clear so that viewing remained unimpaired.

3.4 Flow Calibration.

In order that scour testing could be carried out at pre-determined heads and flows the apparatus was calibrated. That is to say measurements were taken of flows against gate openings over a range of heads. Effective head was taken as the vertical distance between the water level in the scour tank and the water level in the discharge tank or riser pipe. For a given gate setting and head, flows were measured by timing how long the collecting tank took to fill between known levels, see 3.2.3 above. Several readings were taken in each case.

It was found necessary to throttle the glass tube on the outside of the tank in order to minimise oscillations and facilitate readings. This was accomplished by means of small bore tubing, sealed to the end of the glass tube and with its other end sited in a hollow brick. The brick was in turn situated in a part of the tank remote from the impact area of the flow entering the tank via the weir at the end of the scour tank. In calculating the volume of water passing for a given time, allowance was made for the volume of the lever sealing/release system and also for general leakages from the scour tank. In both cases the corrections necessary were minimal.

The calibration curves obtained from this esercise are shown on Figure 3.8. Gate openings are quoted in terms of gate gauge readings. These are the readings on a convenient reference gauge sited immediately adjacent to the gate leaf. The primary purpose of the gauge was to allow flow values obtained to be re-established or intermediate values interpolated.

it can be seen that there are in effect three boundaries to measurement, leaving a central triangular matrix of heads and flows from which to operate. The left, sloping boundary is governed by an effective minimum gate gauge reading of 0.25. The right, sloping boundary indicates the limit of acceptable (stable) flow conditions in the empty scour tank. The lower boundary, rising from a head of 0.3 m to 0.5 m, represents a lower limit of steady surface conditions in the discharge tank.

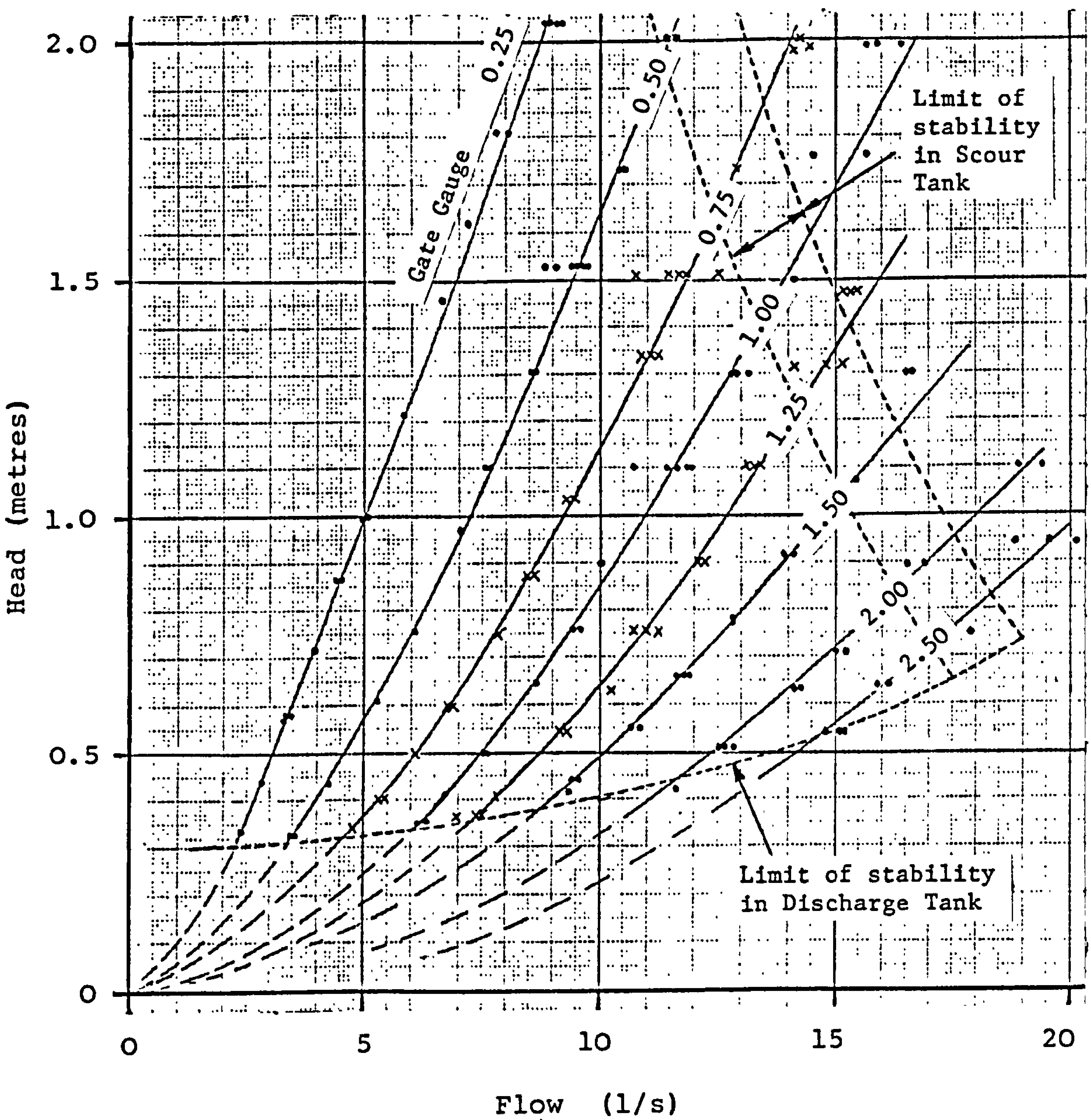


FIGURE 3.8 Scour Apparatus, Flow Calibration Curves.

All calibration readings have been included in Figure 3.8. At least two readings were taken at each head and gate setting. In many cases the figure was higher.

3.5 Final Comments

The above broadly summarises the main features of the apparatus and the principles of its operation. Those aspects and techniques which emerged only and directly, as a result of actual scour testing will be dealt with in Chapter 4 as part of that subject.

CHAPTER 4

SCOUR TEST RESULTS

4.1 Introduction

Once the apparatus had been calibrated, mobile bed material was added to the scour tank and trial runs made over a range of flows and heads. It was found that with the scour tank full of bed material the practical upper limit for flow was 10 l/s. Above this the turbulent action in the plunge pool caused serious splashing over the sides of the scour tank. This further restricted the central triangular matrix which was shown on Figure 3.8 as available for testing. Nevertheless, it was considered that an adequate range of values for flow and head still remained. A network of Flow/head values was selected to give variations of flow at constant head and vice versa. This network of points together with their individual reference numbers is shown on Figure 4.1.

The level of the mobile bed was set at 75 mm below the base of the discharge tank, as shown on Figure 3.1. Initial trials indicated scour patterns very similar to the Form II scour referred to by Kobus et al (1979) and also by Doddiah et al (1953), see Chapter 1, Section 1.5. The typical pattern of scour obtained is shown on Figure 4.2, with arrows indicating idealised directions of flow.

Initially scour progressed very rapidly. The incoming jet removed bed material from the base of the scour hole (A), sweeping it against the downstream face of the plunge pool (B). The force of the jet maintained this face almost vertically and hence the deflected jet rose almost vertically upwards, entraining bed material. Part of the flow then returned downstream (C), re-entraining with the incoming jet and feeding eroded bed material back towards (A). The remainder of the flow passed downstream. This flow deposited out eroded bed material onto sloping face (D)

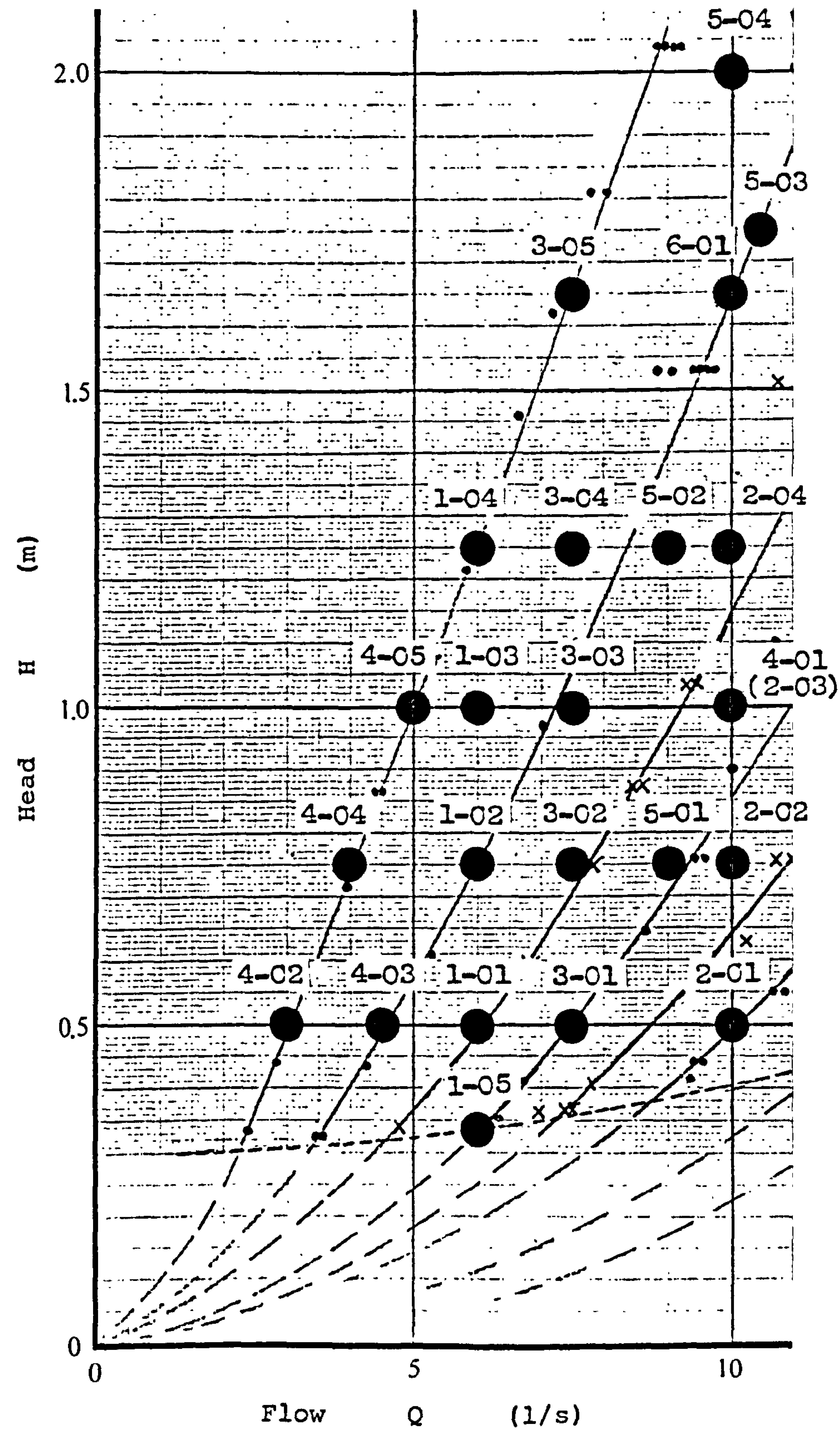
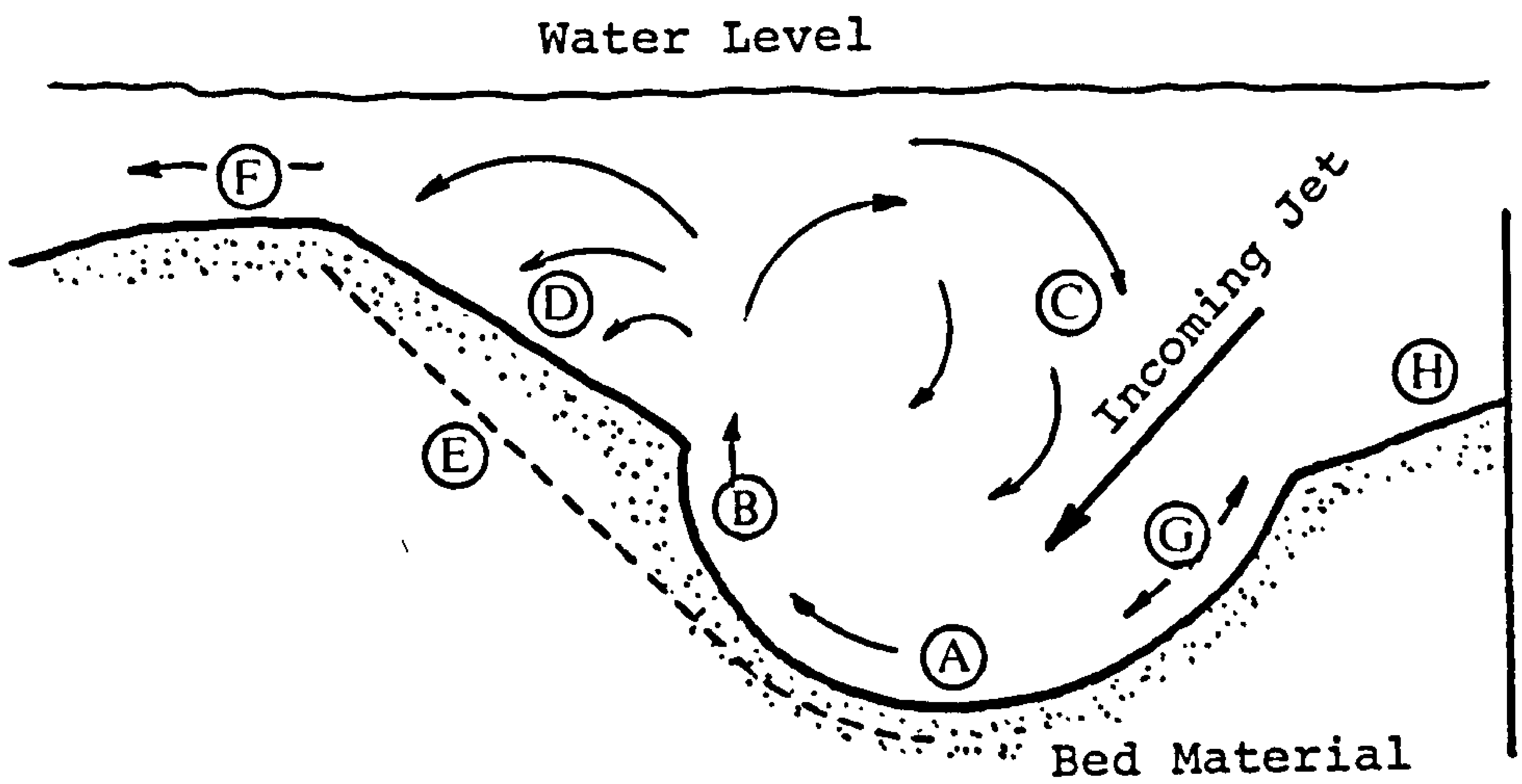


FIGURE 4.1 Scour Test Reference Numbers superimposed on Apparatus Calibration Curves.



A = Erosion

B = Face sustained by force from water

C = Return Current

D = Deposition

E = Lower Sliding Plane

F = Downstream bar

G = Oscillating Flow

H = Tranquil region

FIGURE 4.2 Typical Scour Regime.

with some bed material being carried still further downstream beyond the downstream bar (F).

As the scour developed and the amount of bed material on sloping face (D) increased, the weight would become greater than could be sustained by the force of the jet acting at (B). At this time a lower sliding plane would develop at (E) and the deposited material would slide back, en-masse into the main scour hole and into the path of the main incoming jet. Deposition at (D) would then recommence.

This process repeated itself continually. The best way to assess whether or not the system had stabilised and a state of dynamic equilibrium been reached was to study the rate of material passing downstream over the bar at (F). This appeared to be a somewhat stochastic process and sometimes associated with collapses of face (D). Nevertheless it was found that even in the cases of larger scours stability had, for all practical purposes, been reached by about 90 minutes.

At the upstream limit of the scour hole the flows at (G) showed an interesting oscillating motion with particles of bed material moving rapidly backwards and forwards. At (H) the bed material was motionless.

At the end of a test, once flows had been turned off, both upstream and downstream faces of the plunge pool would collapse to the natural angle of repose of the bed material (approx, 33 to 35°).

The scour process summarised above meant that there were in fact two obvious scour depths which could be measured. The first was the depth to point (A), the dynamic depth of scour. The second was the maximum depth of the hole once flow had been turned off and the sides of the hole collapsed in. In fact there was also a third depth. As the base of the scour hole was permeable, the jet was able to penetrate and, at times, move stones below level (A). This was considered to be the maximum depth of jet effect and was also recorded. It was found that the lower limit of bed movement, continued round in this way, coincided with the line of sliding plane (E) which also, in effect, represented a lower limit of particle movement.

The measurements taken in each test run, are shown in Figure 4.3. The scour depths referred to above are shown as d_1, d_2 and d_3 as measured below the datum line. The datum line was in turn fixed as the level of the base of the discharge tank. The tailwater depth h_2 above the datum line could be added to depths d_1, d_2 and d_3 to obtain corresponding scour depths D_1, D_2 and D_3 below tailwater level. The head drop, H, could be calculated by subtracting h_2 from h_3.

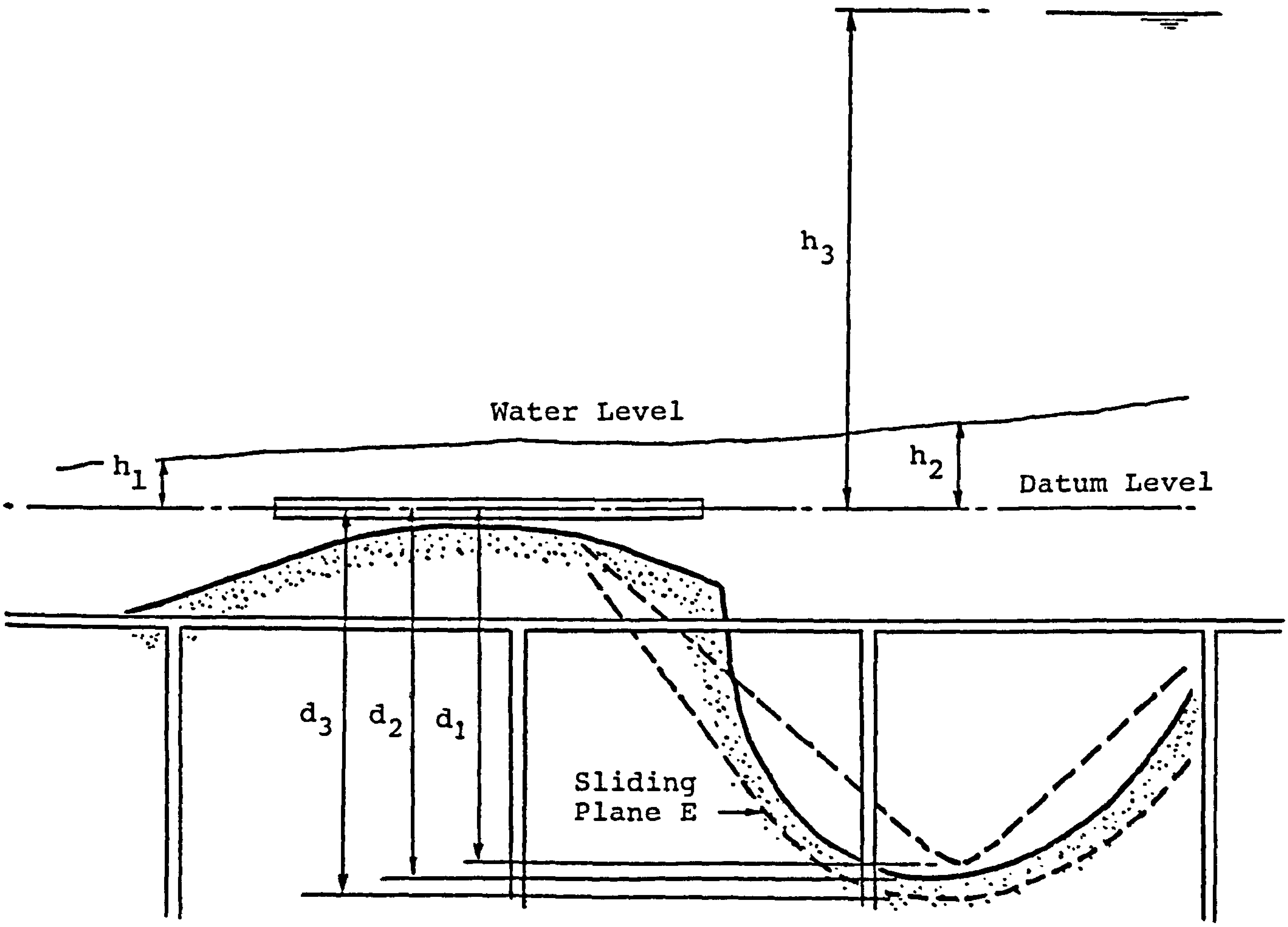
The readings taken in the various tests together with the associated values of D_1, D_2, D_3, H and Q, are given in Appendix A.

The remainder of this Chapter deals with the results of the two dimensional tests.

4.2 Ultimate Depth Testing without Air Entrainment

As has been discussed earlier, it was considered that the variations in the effects of flow and head drop on the scour process, as recorded by other authors, may have been due to variations in air entrainment by the jet. The first series of tests therefore varied flow and head drop but excluded all air from the scour processes. The tests carried out are represented by the points shown on Figure 4.1.

Once stability had, to all intents and purposes, been reached in a particular test, strips of flexible sealing compound were used to mark the scour profiles on the perspex side of the tank. Profiles corresponding



d_1 = Collapsed (no flow) depth

d_2 = Depth to top of bed movement

d_3 = Depth to bottom of bed movement

h_1 = Downstream water height

h_2 = Water height over plunge pool

h_3 = Height to water column in discharge tank

All measurements referred to datum level as shown

FIGURE 4.3 Scour Reference Measurements.

to both the dynamic scour depth (d_2) and the maximum effective scour depth (d_3) were marked and photographed. Once the flow had been turned off and the bed material collapsed to its natural angle of repose, the profile corresponding to scour depth (d_1) was added and the tank side re-photographed. Photographs of typical results from this series of tests are shown in Figures 4.4 to 4.7.

Typical, processed results from this series of tests are shown in Figure 4.8. This plots scour depth (D_3) below tailwater level against both Head Drop (H) and flow (Q), on log/log scales.

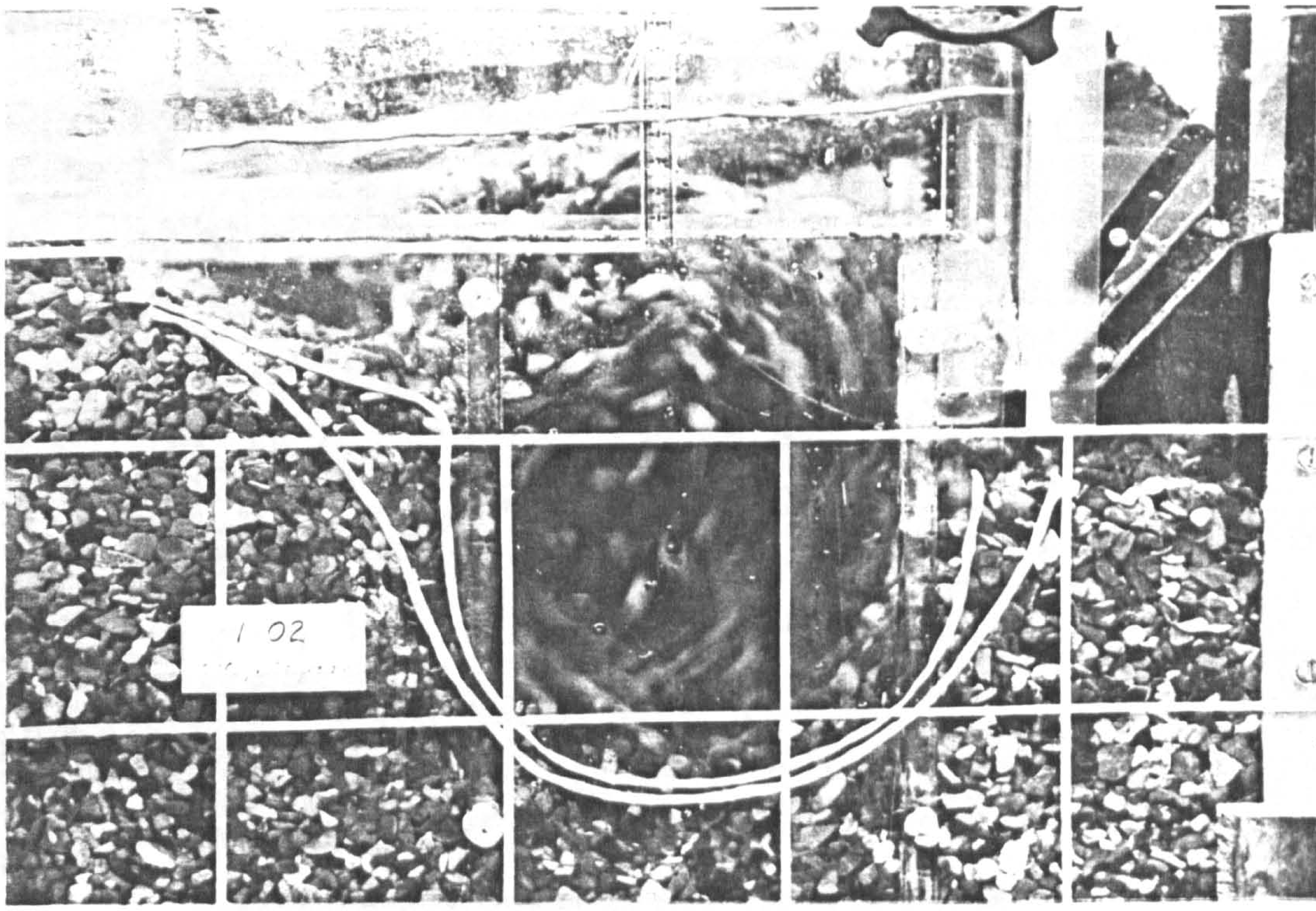
Linear regression was used to establish the slopes of these lines, together with similar lines for (D_1) and (D_2). The mean slopes and correlation coefficients from this exercise are given in Table 4.1. It can be seen from this that the mean slope of depth as a function of head (H) is effectively zero while the mean slope of depth as a function of flow (Q) is effectively unity. Thus equation:

$$D = K\, q^x\, H^y \qquad \text{(See Chapter 1)}$$

becomes $$D = Kq$$

It can be seen from Table 4.1 that the correlations of depth with head are much more variable than those of depth with flow. This is probably due to the small numbers of results used in each depth against head correlation. The results are nevertheless still considered to be valid.

The result that, without air, scour seemed to be purely a function of flow was a rather surprising one, particularly as one possibility being investigated was that it might have been an equal function of flow and head, that is a function of jet power.



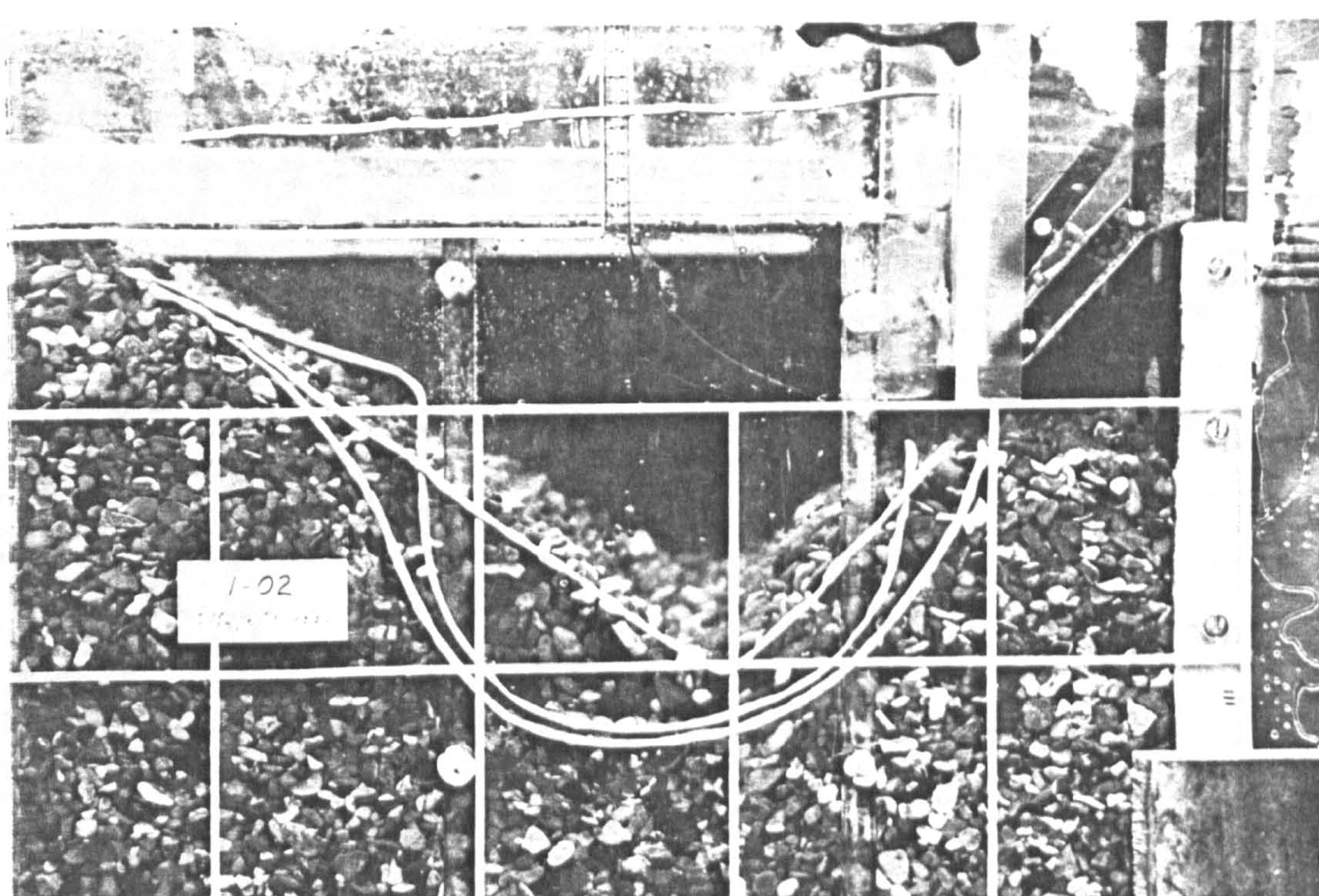
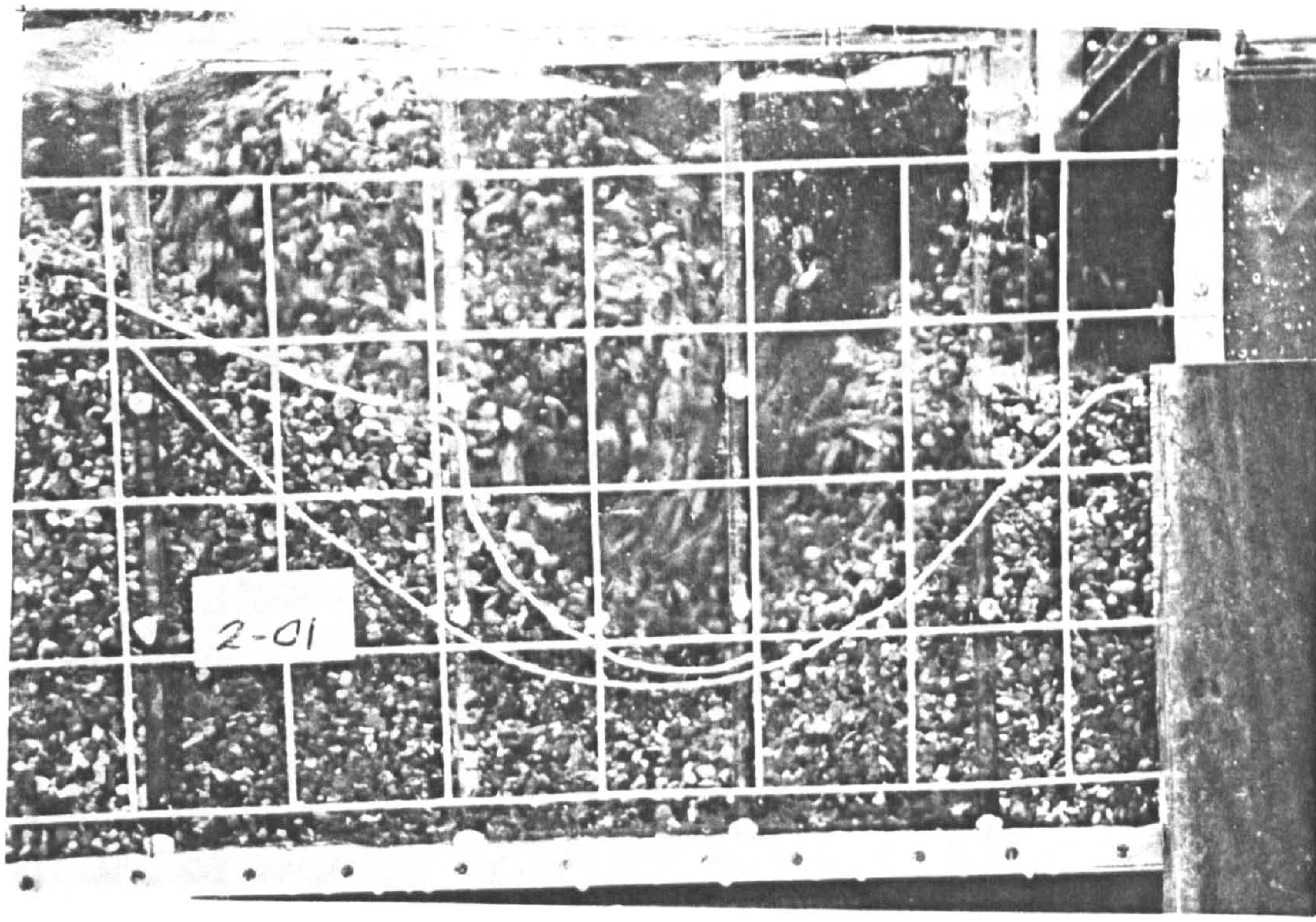


FIGURE 4.4 Scour Results for Test 1-02 (Q=6 l/s, H=0.740m, Air=zero).



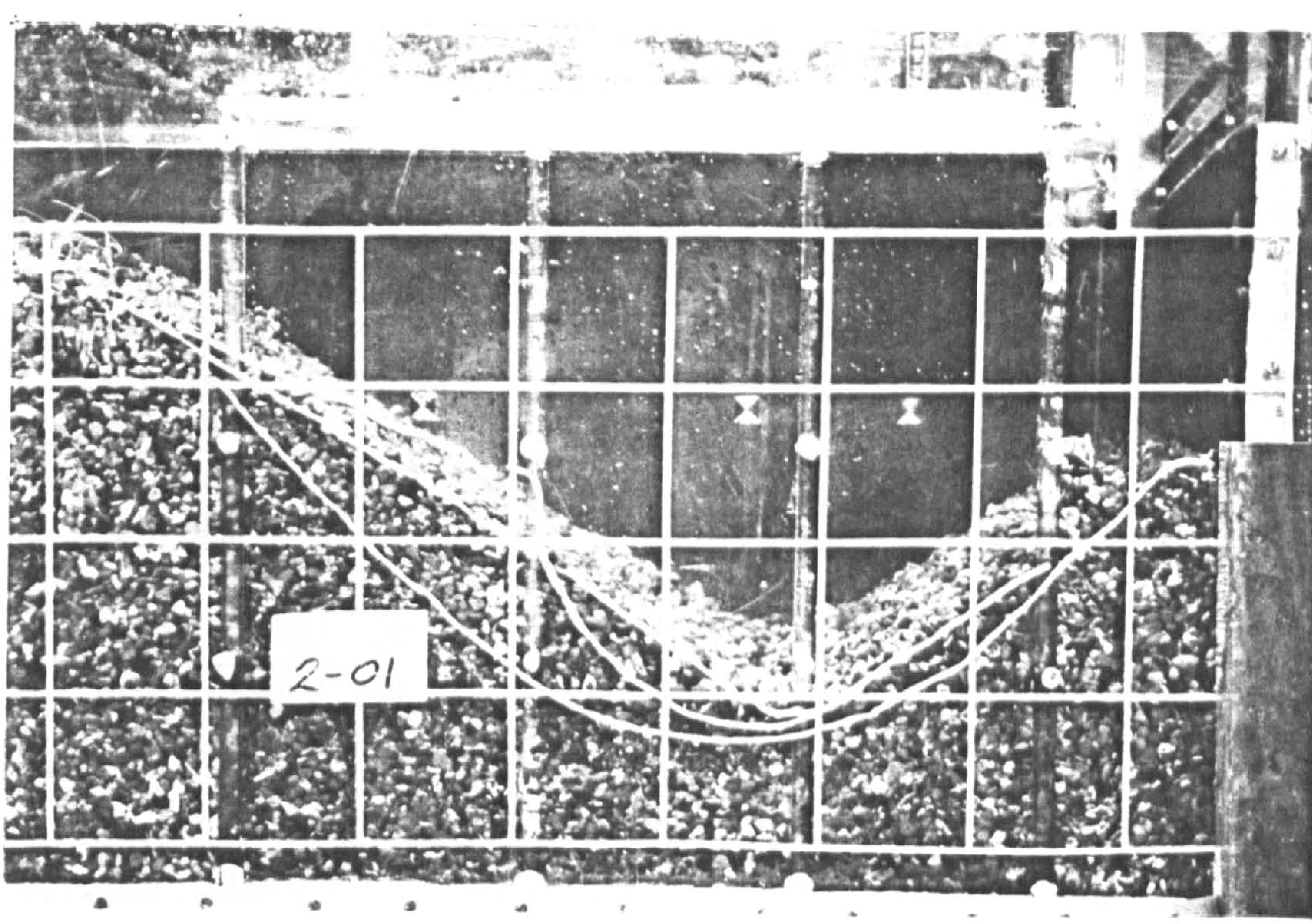
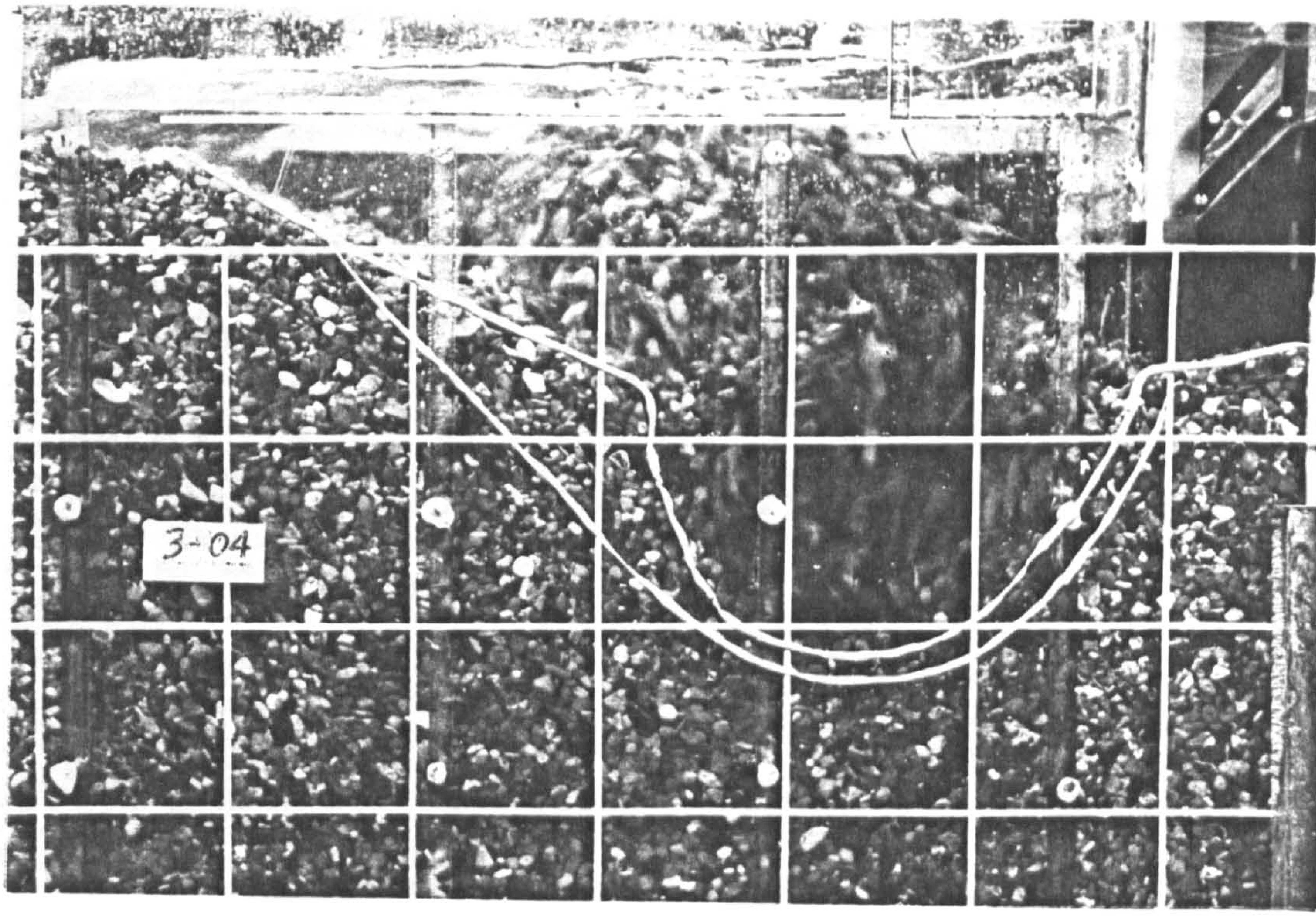


FIGURE 4.5 Scour Results for Test 2-01 (Q=10 l/s, H=0.520m, Air=zero).



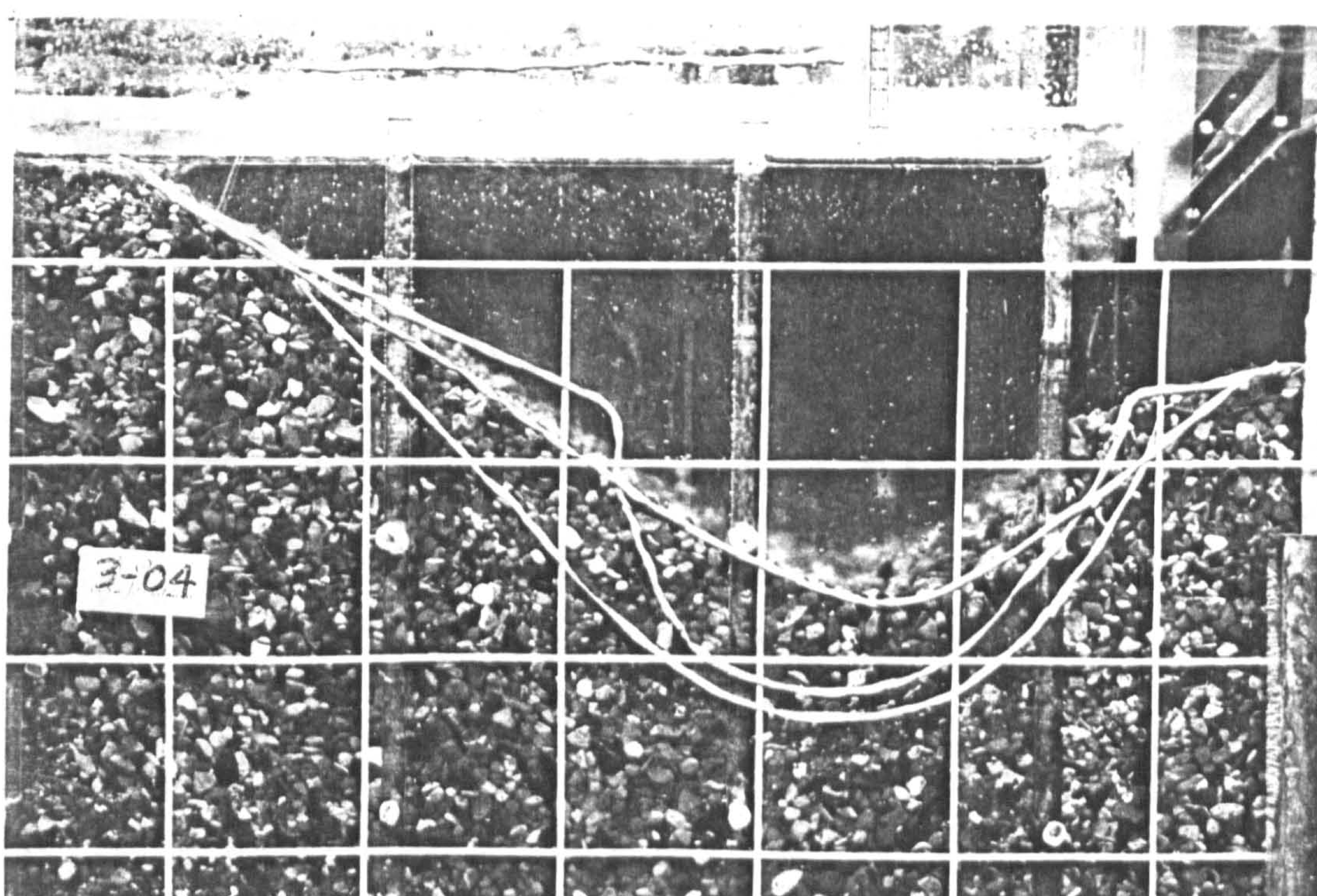


FIGURE 4.6 Scour Results for Test 3-04 (Q=7.5 l/s, H=1.245m, Air=zero).

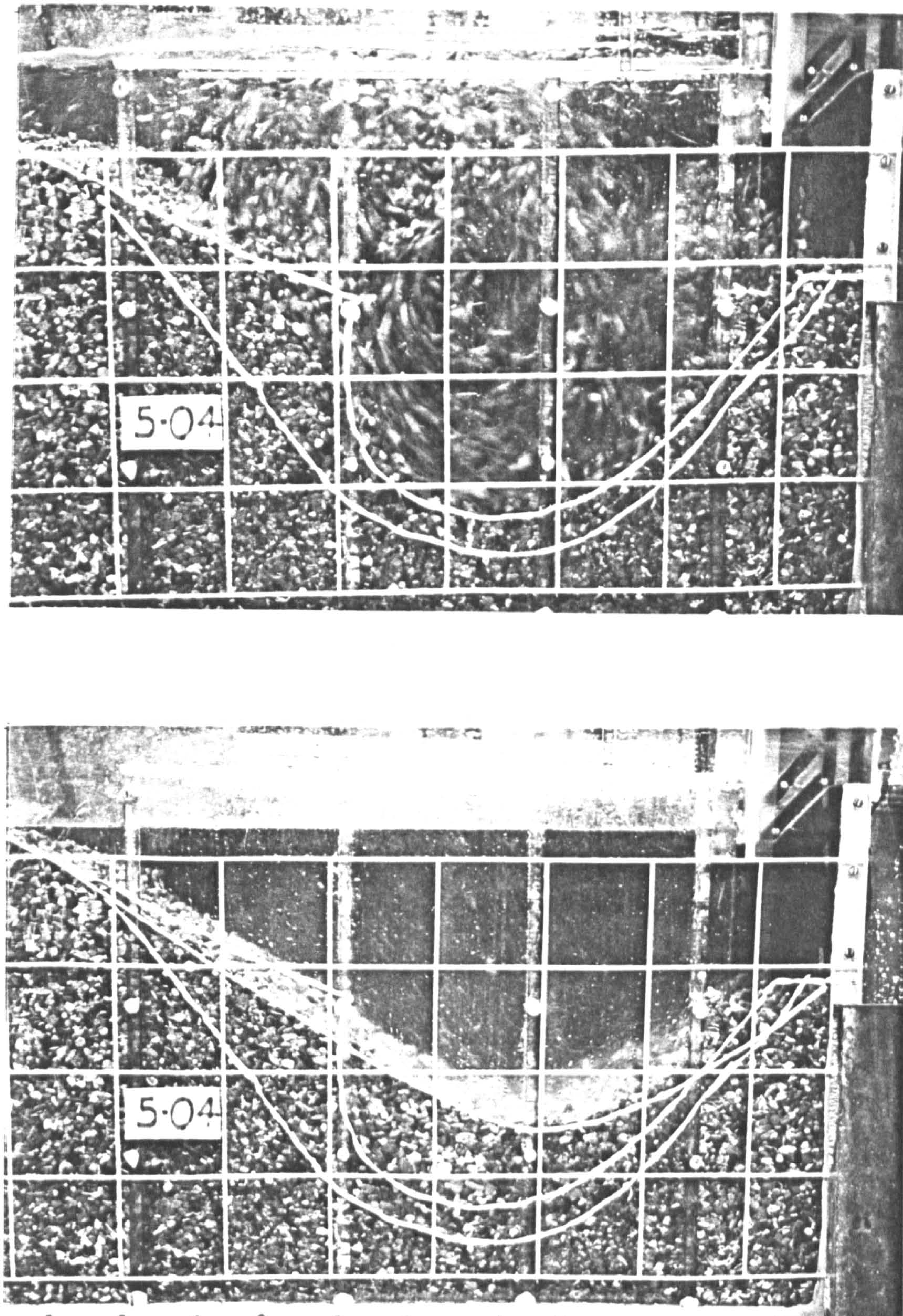


FIGURE 4.7 Scour Results for Test 5-04 (Q=10 l/s, H=1.995m, Air=zero).

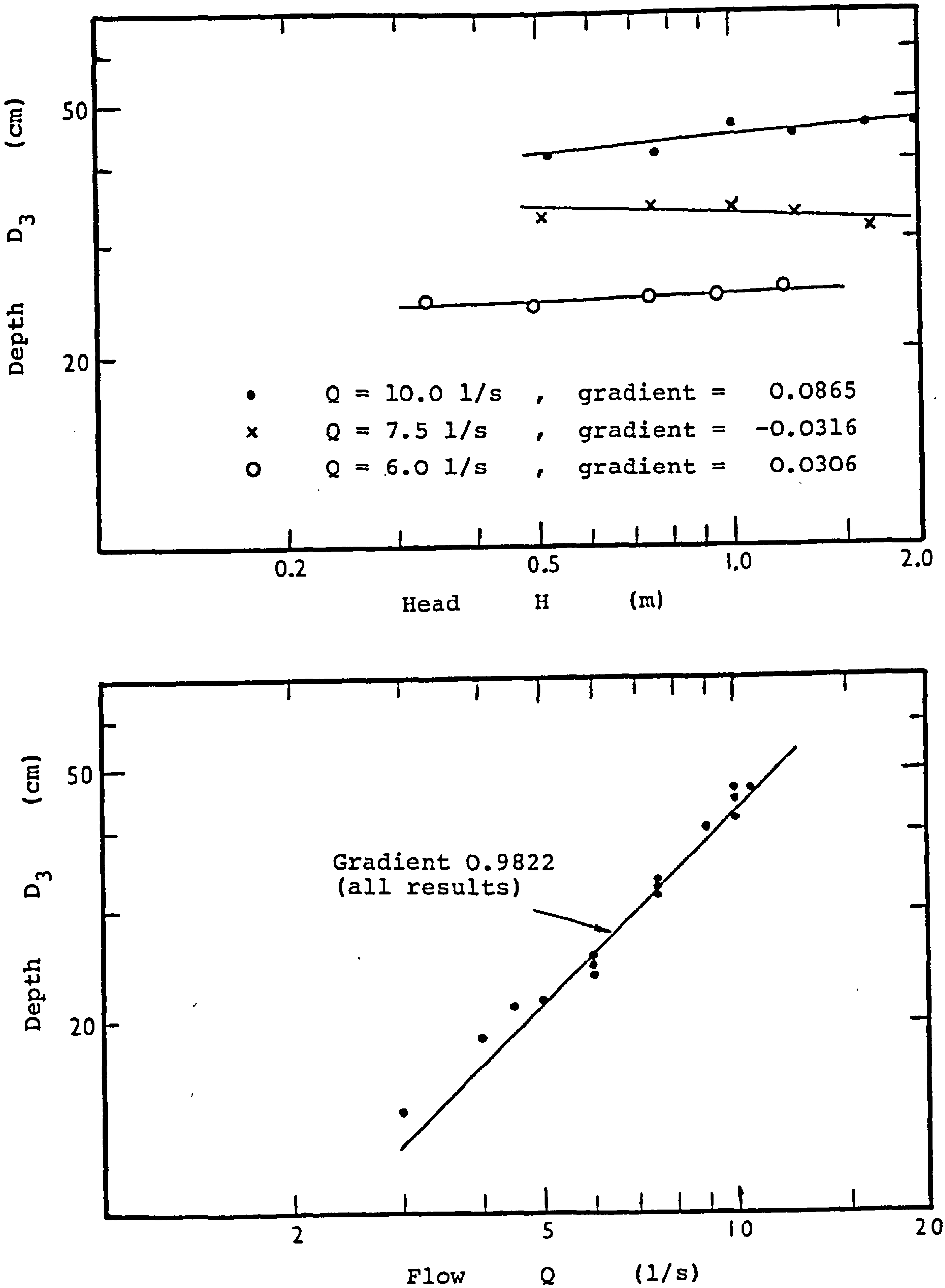


FIGURE 4.8 Variation of Scour Depth, D_3, with Flow and Head Drop for Non-Aerated Flows.

Flow (l/s)	Head Range (cm)	No. of Results	Scour Depth	Gradient of Correlation	Coeff. of Correlation
6	49-120	5	D_1	- 0.0184	- 0.2480
6	49-120	5	D_2	0.0239	0.8998
6	49-120	5	D_3	0.0306	0.6853
7.5	50.5-164.5	5	D_1	- 0.0808	- 0.8312
7.5	50.5-164.5	5	D_2	- 0.0261	- 0.3598
7.5	50.5-164.5	5	D_3	- 0.0316	- 0.4667
10.0	52 -199.5	6	D_1	- 0.0805	- 0.7782
10.0	52 -199.5	6	D_2	- 0.0428	0.7453
10.0	52 -199.5	6	D_3	0.0865	0.8543
		Mean Gradient		- 0.0060	

Correlation of Scour Depth against Head Drop (H)

Flow (l/s)	Head Range* (cm)	No. of Results	Scour Depth	Gradient of Correlation	Coeff. of Correlation
3-10.5	33-199.5	23	D_1	0.9323	0,9647
3-10.5	33-199.5	23	D_2	0.9817	0.9934
3-10.5	33-199.5	23	D_3	0.9822	0.9883
		Mean Gradient		0.9654	

Correlation of Scour Depth against Flow (Q)

(*Head Range added for completeness although the correlation was only against Flow).

TABLE 4.1 Correlation of Non-aerated Scour Depths against Head Drop (H) and Flow (Q).

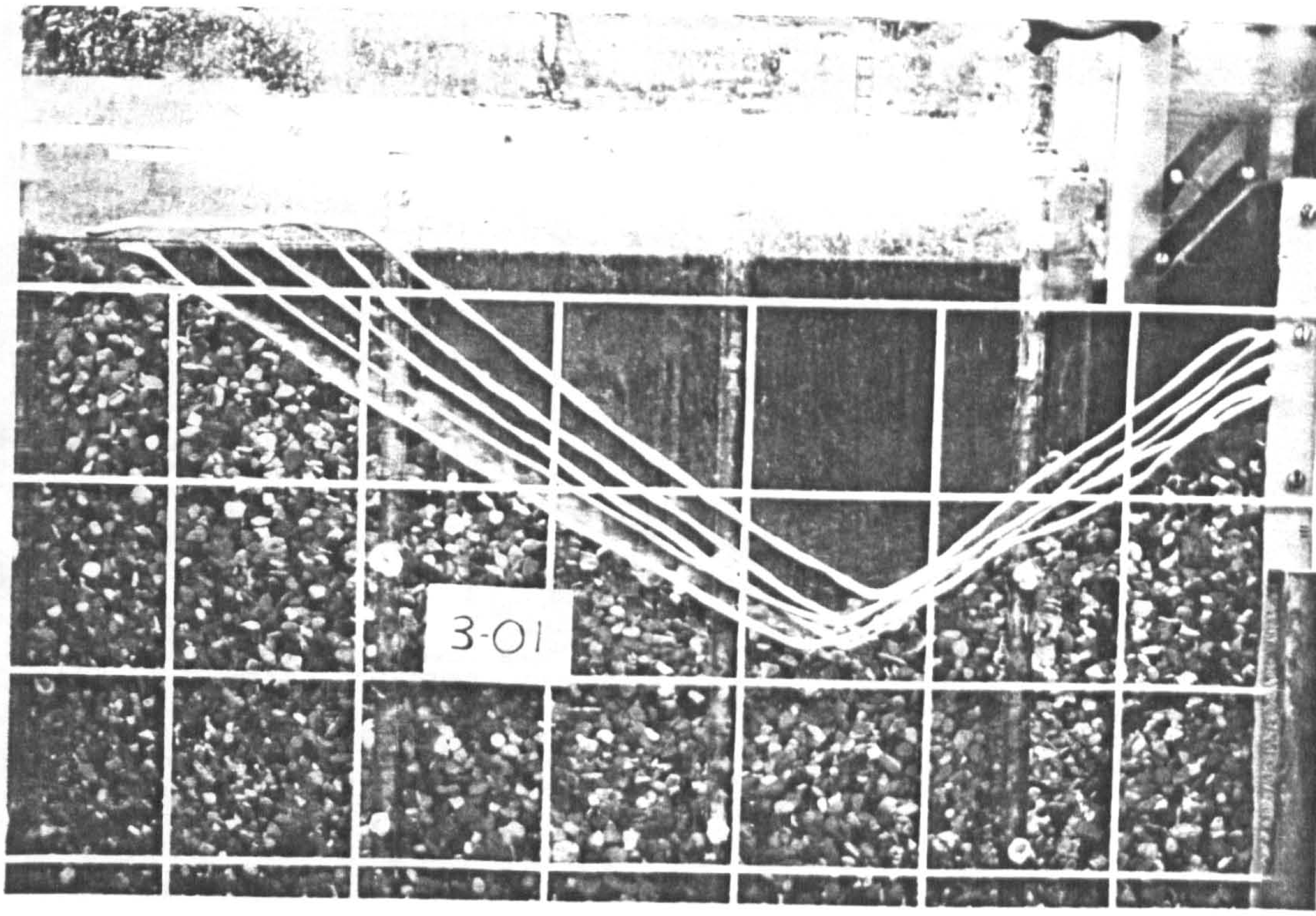
It was decided, before beginning tests with entrained air, to carry out a series of tests measuring the rate of scour as a function of head drop. This was to determine whether, although ultimate scour may be a function of flow alone, the rate at which that depth was reached could also be a function of head drop. These tests and their results are described below.

4.3 Rate of Scour Without Air

In order to establish the rate of scour against varying head drop (H) a constant flow of 7.5 l/s was selected for all tests and the head varied. In effect, tests number 3.01 to 3.05 on Figure 4.1 were re-run. In each case the flow was turned off at intervals throughout the tests and the collapsed bed profile marked on the side of the tank. The first run in each case was for 1 minute. After marking, the test was re-run for another 2 minutes and so on in intervals of 5, 10 and 20 minutes. Profiles obtained in this way for tests 3.01 to 3.04 are shown on Figures 4.9 to 4.10. it is accepted that timings, particularly of short periods, could not be precise owing to the start up time and drain down time of the discharge tank, although only part of the discharge and drain down times would have affected the results. Great care was also taken to ensure consistency between tests.

Scour profile measurements were made every time the flow was turned off and these were used to compute the total volume of materials scoured below original bed level. As before the results are presented in tabular form in Appendix A. They are also presented graphically in Figure 4.11.

The results indicated that head drop (H) does not appear to have any significant effect on the rate of scour just as the previous tests showed that it had no significant effect on ultimate scour depths.



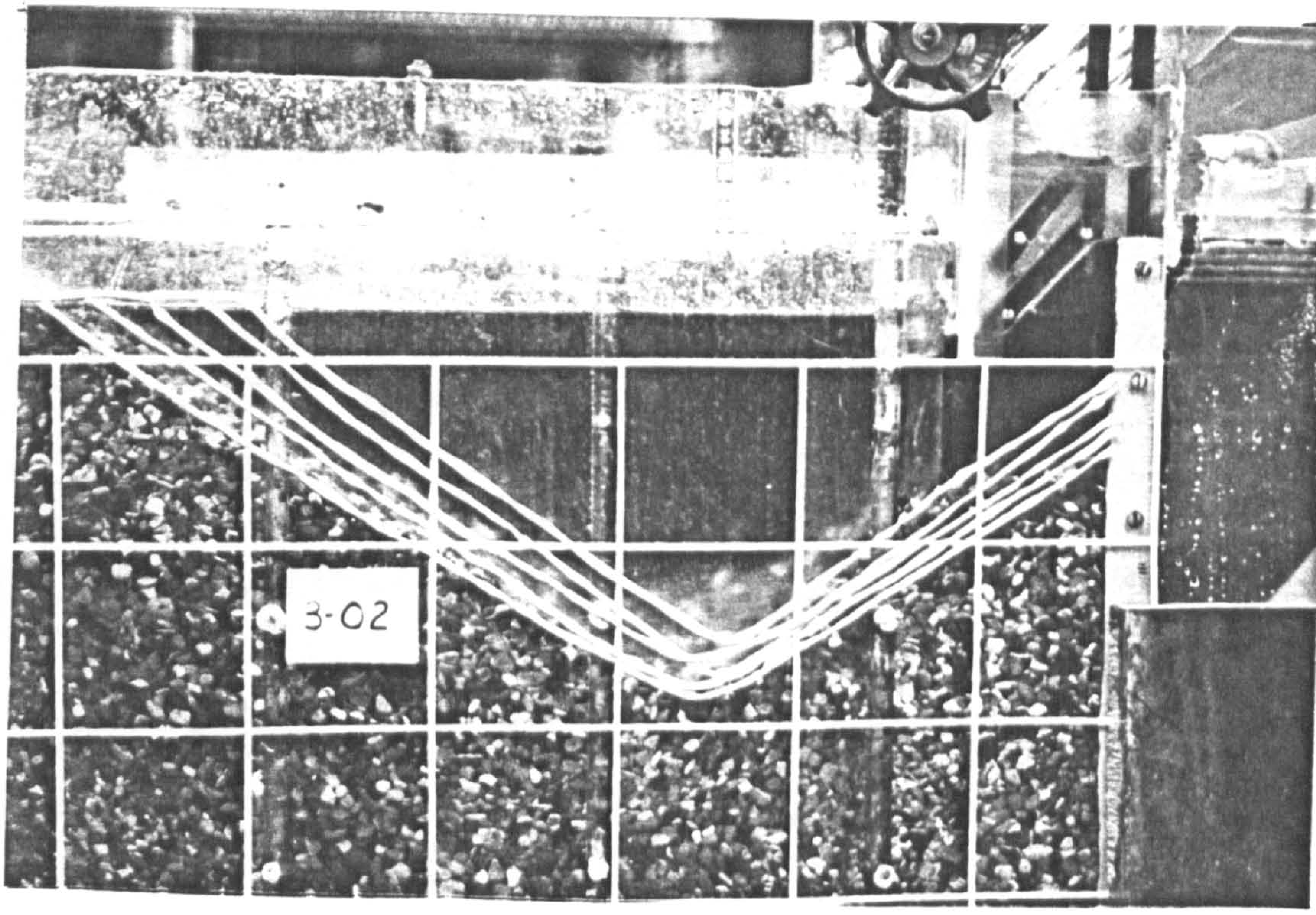
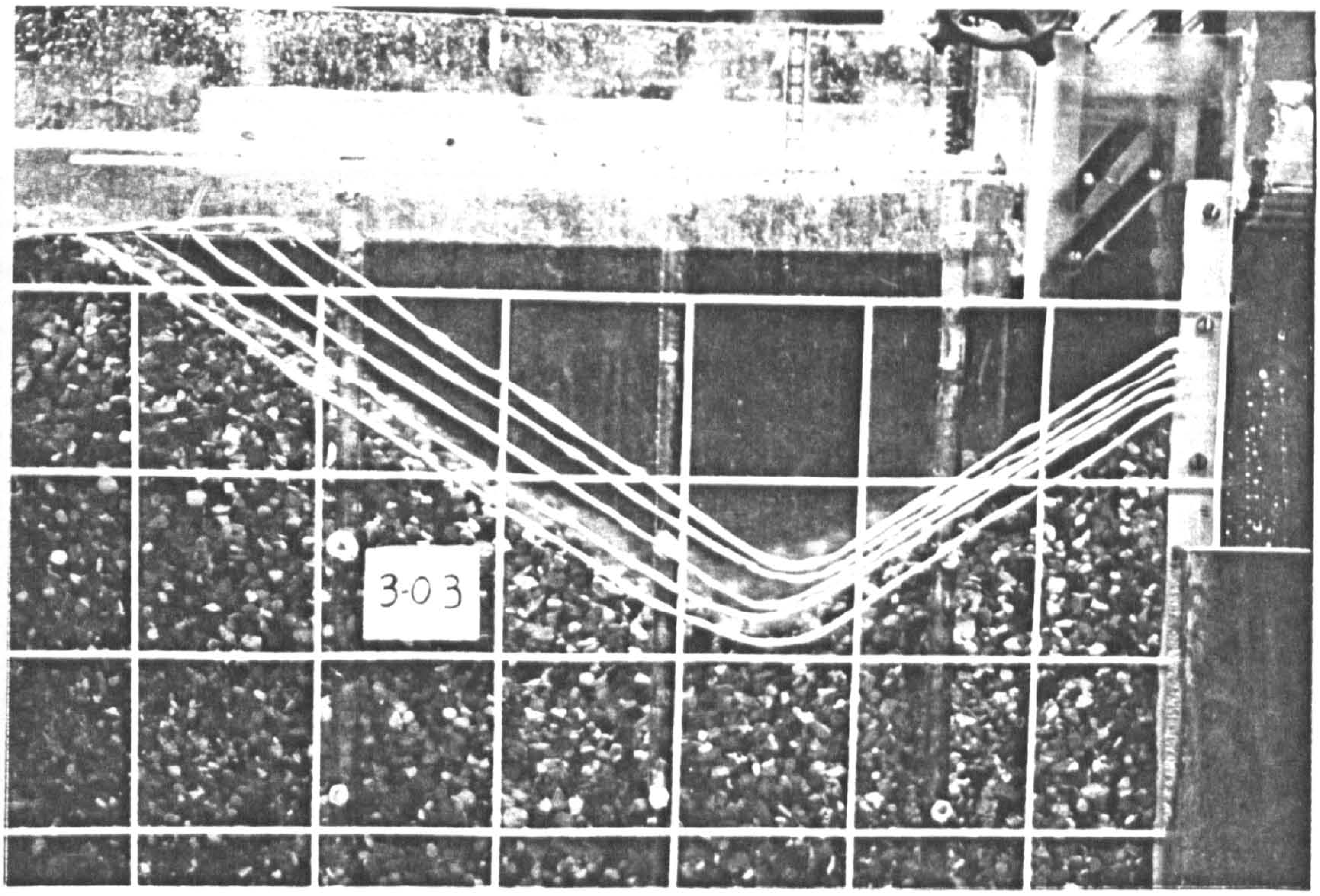


FIGURE 4.9 Rate of Scour Results for Tests 3-01 and 3-02.



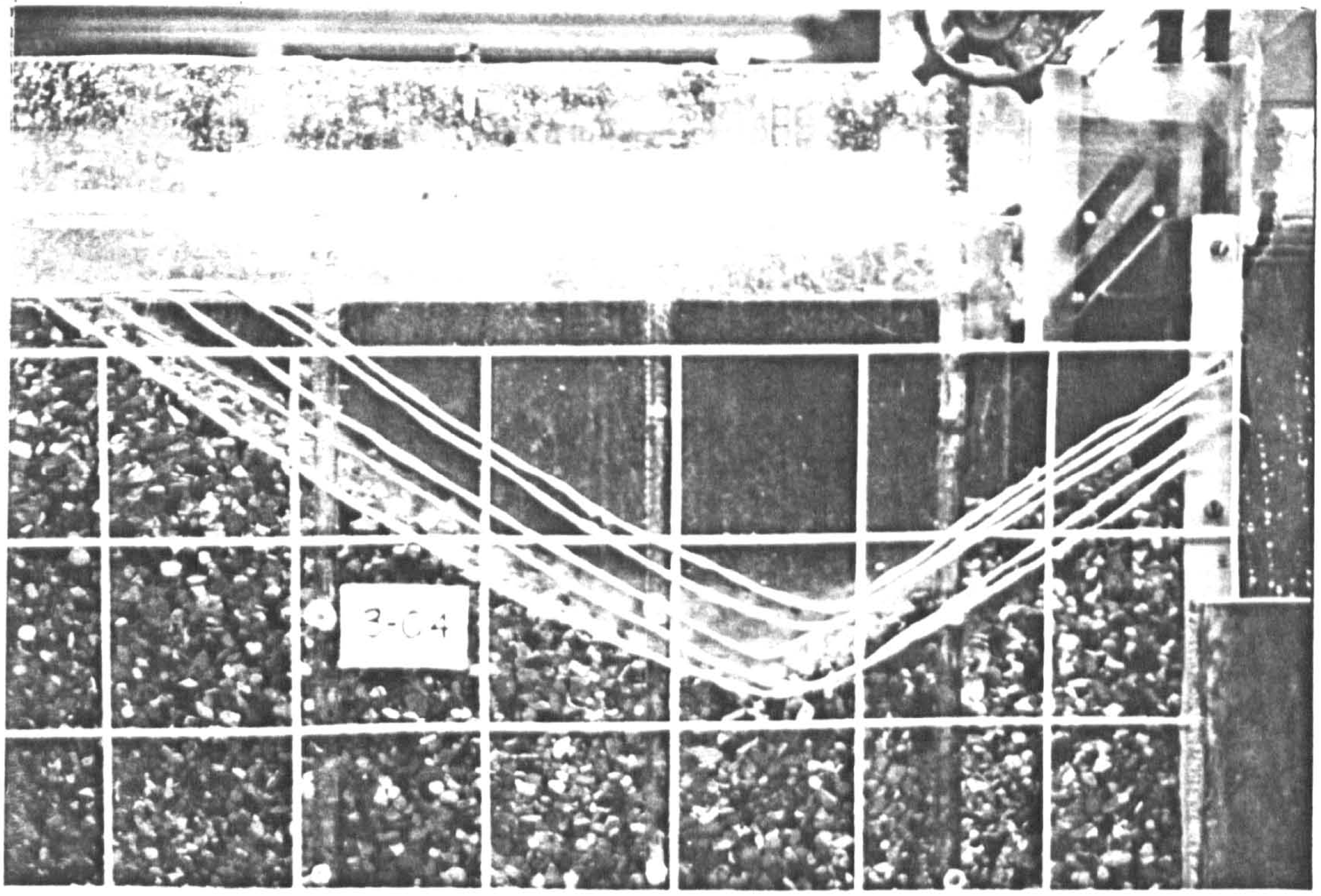


FIGURE 4.10 Rate of Scour Results for Tests 3-03 and 3-04.

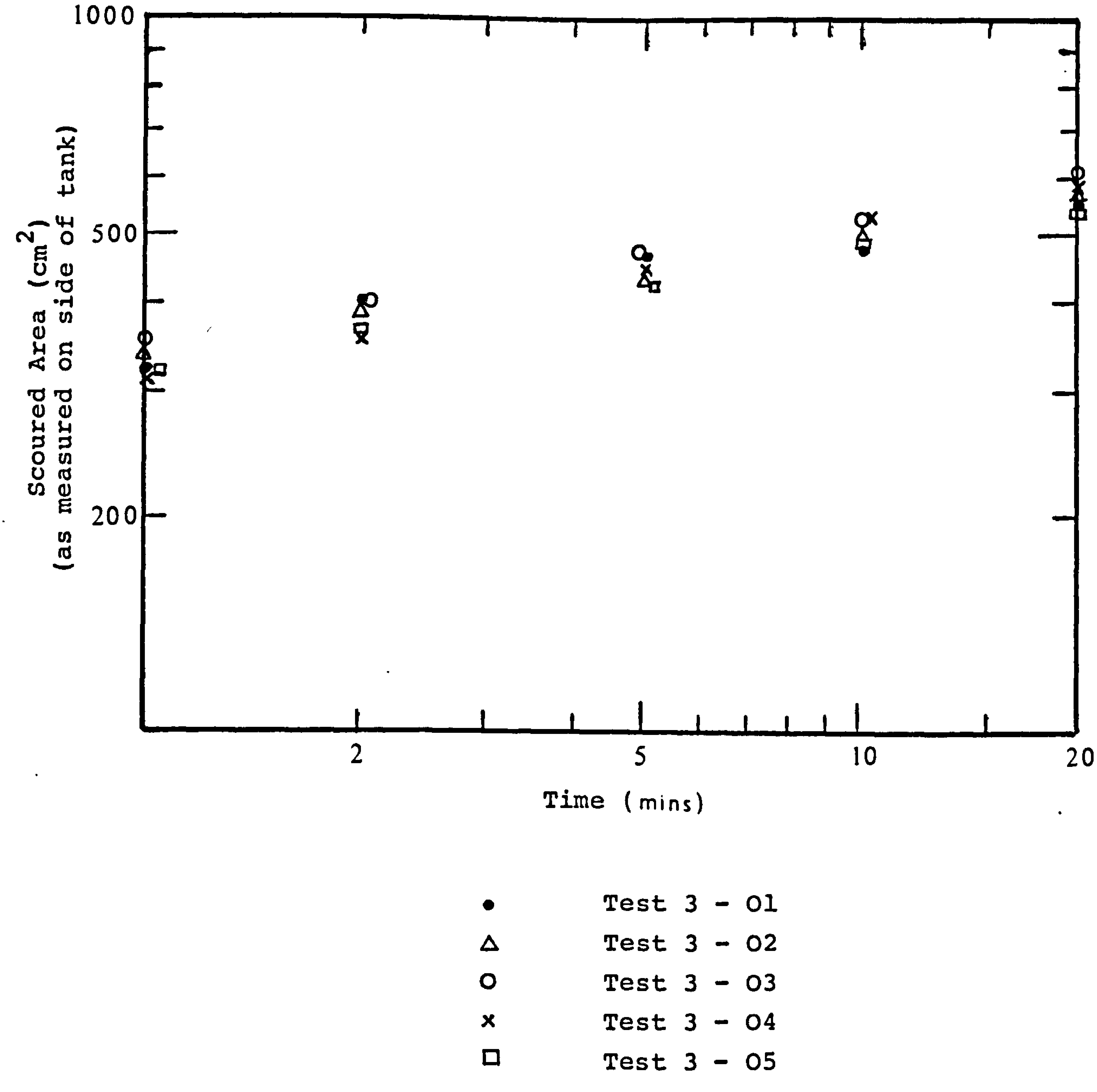


FIGURE 4.11 Comparison between Rate of Scour Test Results.

4.4 Ultimate Depth Testing with Air Entrainment

In order to compare the results that were obtained using a water jet alone with those that would occur with entrained air, the range of tests described in Section 4.2 were re-run with air entrainment. The system for entraining air in the jet is described in Sections 3.2.1 and 3.2.5 of Chapter 3.

The intention of carrying out the air entrained tests was to try and reproduce the conditions that would prevail were the jet to fall a height (H) and entrain air naturally on its entry to water. This is, after all, the condition which occurs normally with jets from ski jumps, overfalls and flip buckets.

In order to reproduce the amounts of air that would entrain naturally under these conditions, recourse was made to the air entrainment formula of Ervine described in Sections 2.3.7 and 2.4 of Chapter 2. Assuming that the air/water ratio:

$$\beta = 0.13 \left(\frac{H}{t}\right)^{0.446} \left(1 - \frac{1.1}{v}\right)$$

$$\text{if } v = \sqrt{2gH} \quad \text{(approx)}$$

$$\text{and } t = \frac{q}{\sqrt{2gH}}$$

$$\text{then } \beta = 0.13 \left(\frac{H\sqrt{2gH}}{q}\right)^{0.446} \left(1 - \frac{1.1}{\sqrt{2gH}}\right)$$

this reduces to

$$= 0.2525 \frac{H^{0.669}}{q^{0.446}} \left(1 - \frac{0.248}{H^{0.50}}\right)$$

This could then be used to derive the amount of air (Qa in l/s) to be introduced into a water flow (Qw in l/s) on the model, for any combination of head drop (H) and flow (Q). In the formula above, unit flow q is in m^2/s. The relationship between this and the model flow Qw in a 0.30 m wide flume is:

$$q = Q/1000 \times 0.3$$
$$= Q/300$$

therefore

$$q^{0.446} = \frac{Qw^{0.446}}{12.7291}$$

Substitution in the reduced Ervine expression gives:

$$\frac{Qa}{Qw} = 0.2525 \times 12.7291 \left(\frac{H^{0.669}}{Qw^{0.446}}\right)\left(1 - \frac{0.248}{H^{0.50}}\right)$$

So that

$$Qa = 3.2141 \quad Qw^{0.554} \, H^{0.669} \left(1 - \frac{0.248}{H^{0.50}}\right)$$

where Qa = Air flow (l/s)
Qw = Water flow (l/s)
H = Head drop (m)

This expression was used to calculate the amounts of air to be introduced in each test, according to the values of Qw and H, in order to simulate that which would be entrained naturally by free falling jets. It was found that in the cases of tests 1-01, 1-05, 4-02 and 4-03, the amounts of air were below the lower measuring limit of the rotameter, hence these tests could not be used, see Figure 4.1. This did not, however, significantly affect the range of tests available. The ratios of air to water (β) found to be appropriate in the cases of the tests carried out varied from 0.474 to 1.567.

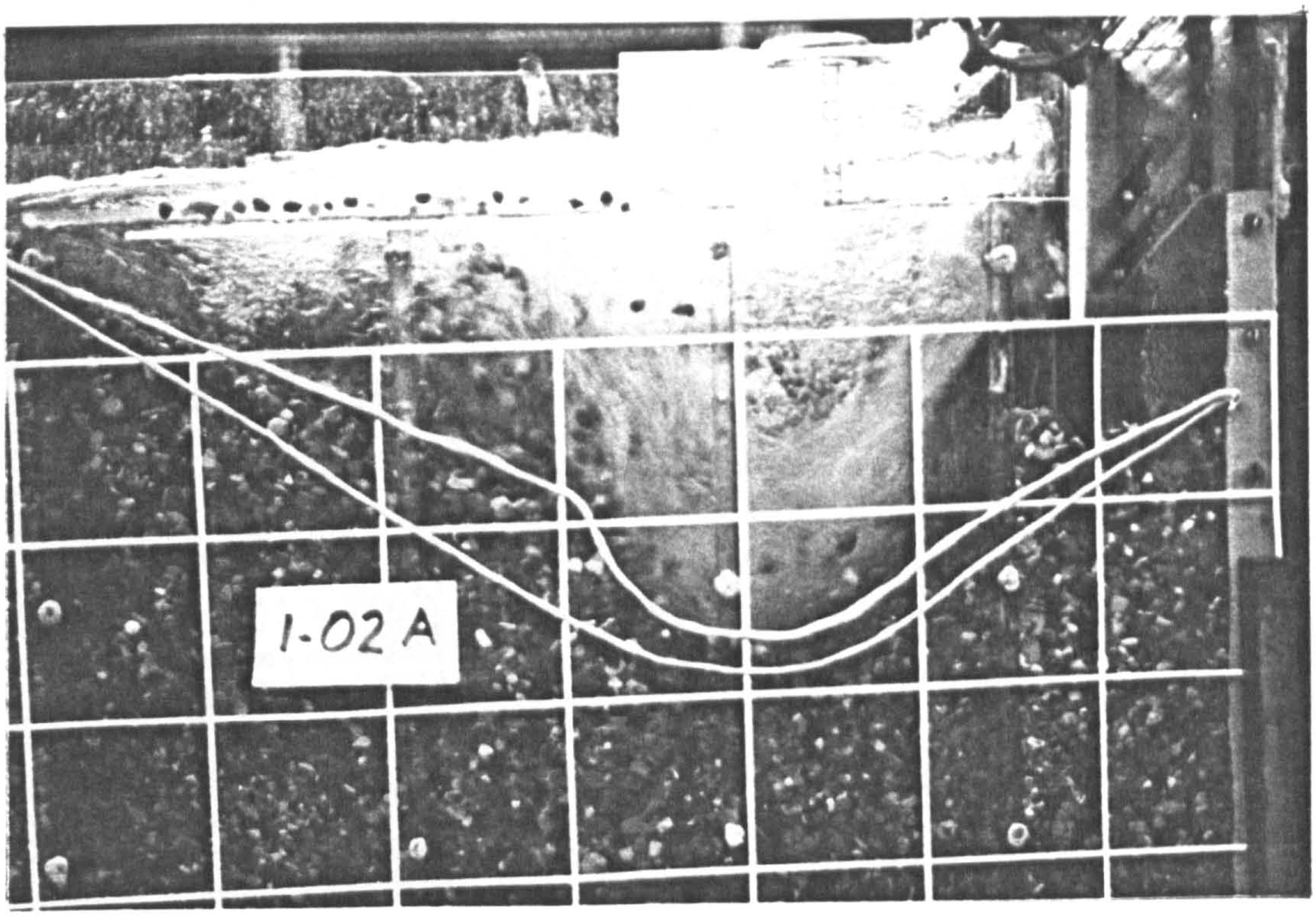
It was found when introducing air into the scour tests that in the early stages of scour development, water level fluctuations caused some instability of the rotameter cone. Once appreciable scour had developed, after say 10 to 15 minutes, the cone remained fairly steady, though regular checks were made both on the rotameter reading and on the water column level in the discharge tank, throughout the tests. Back pressures on the rotameter were generally in the order of 30 to 40 mm of water, hence it was not necessary to modify the calibration curves.

Typical photographic results from these tests are shown in Figures 4.12 to 4.15. These represent the equivalent aerated tests to those non-aerated tests depicted in Figures 4.4 to 4.7. It can be seen that scour profiles are generally flatter than those from the non-aerated tests. It was mentioned in Section 4.1 that in the initial, non-aerated, tests the water jet deflected at (B), see Figure 4.2, was able to support the bed material deposited at (D). The aerated flow, however, seemed to penetrate the face at (B) and burst upwards through (D). Generally greater volumes of bed material appeared to be removed than for the equivalent non-aerated conditions, due largely to the greater horizontal spread of the scour. In fact, in many cases the scour profiles with aeration seemed to be in a Form I pattern (Kobus, 1979) rather than the non-aerated flow, Form II patterns.

Typical processed results from this series of tests are shown in Figure 4.16. This plots scour depth (D_3) below tailwater level against both head drop (H) and flow (Q) on log/log scales. It is in fact the equivalent series of plots to those shown in Figure 4.8 for non-aerated flows. It can be seen, however, that the introduction of air has significantly affected the slopes of the lines.

Once again linear regression was used to establish the slopes of these lines, together with similar lines for (D_1) and (D_2). The mean slopes and correlation coefficients from this exercise are given in Table 4.2. It can be seen that there is much more variation between slopes than was the case with non-aerated flows (Table 4.1). In the expression:

$$D = K\, q^x\, H^y$$



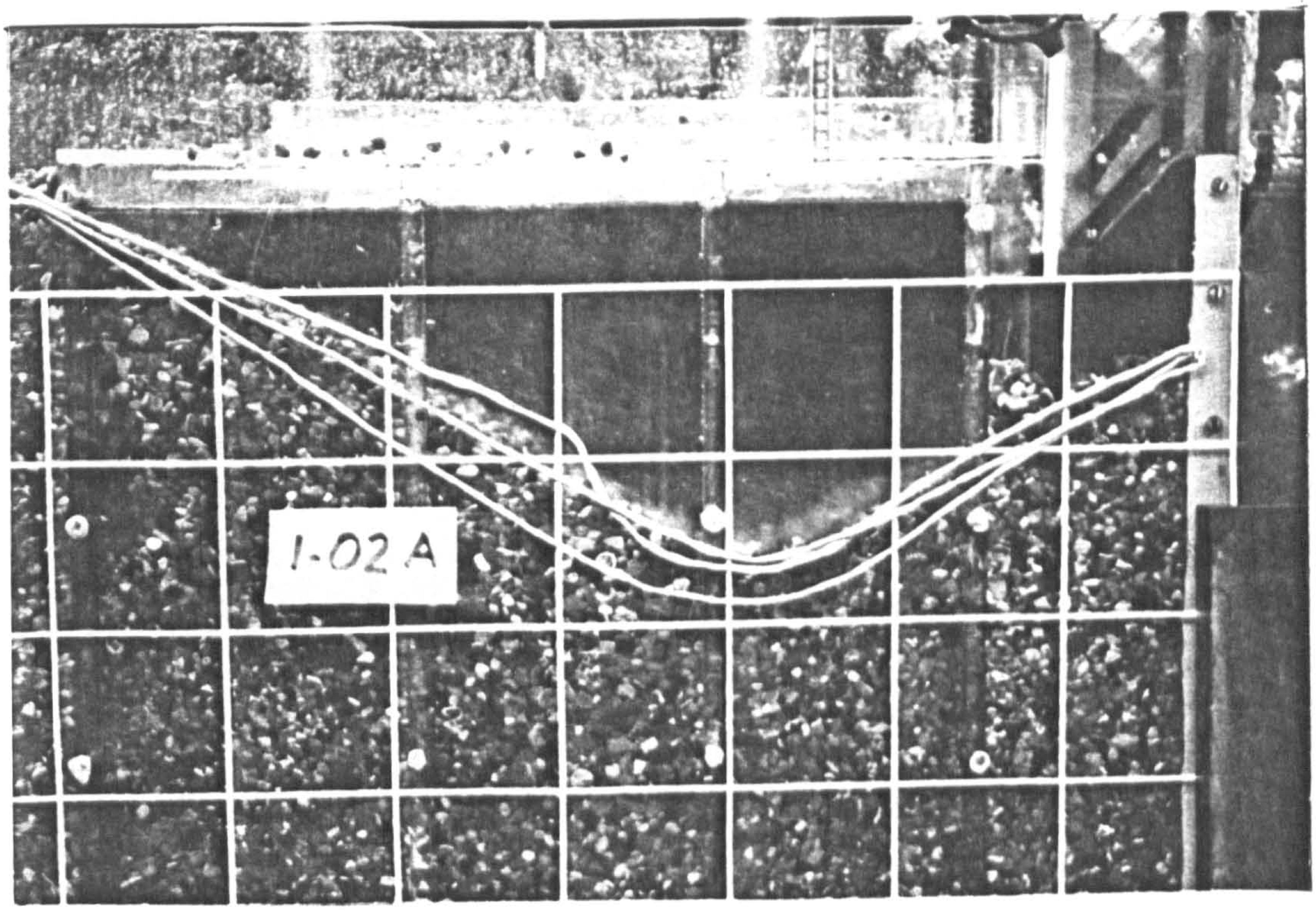


FIGURE 4.12 Scour Results for Test 1-02A (Q=6 l/s, H=0.750m, Air=5.15 l/s).

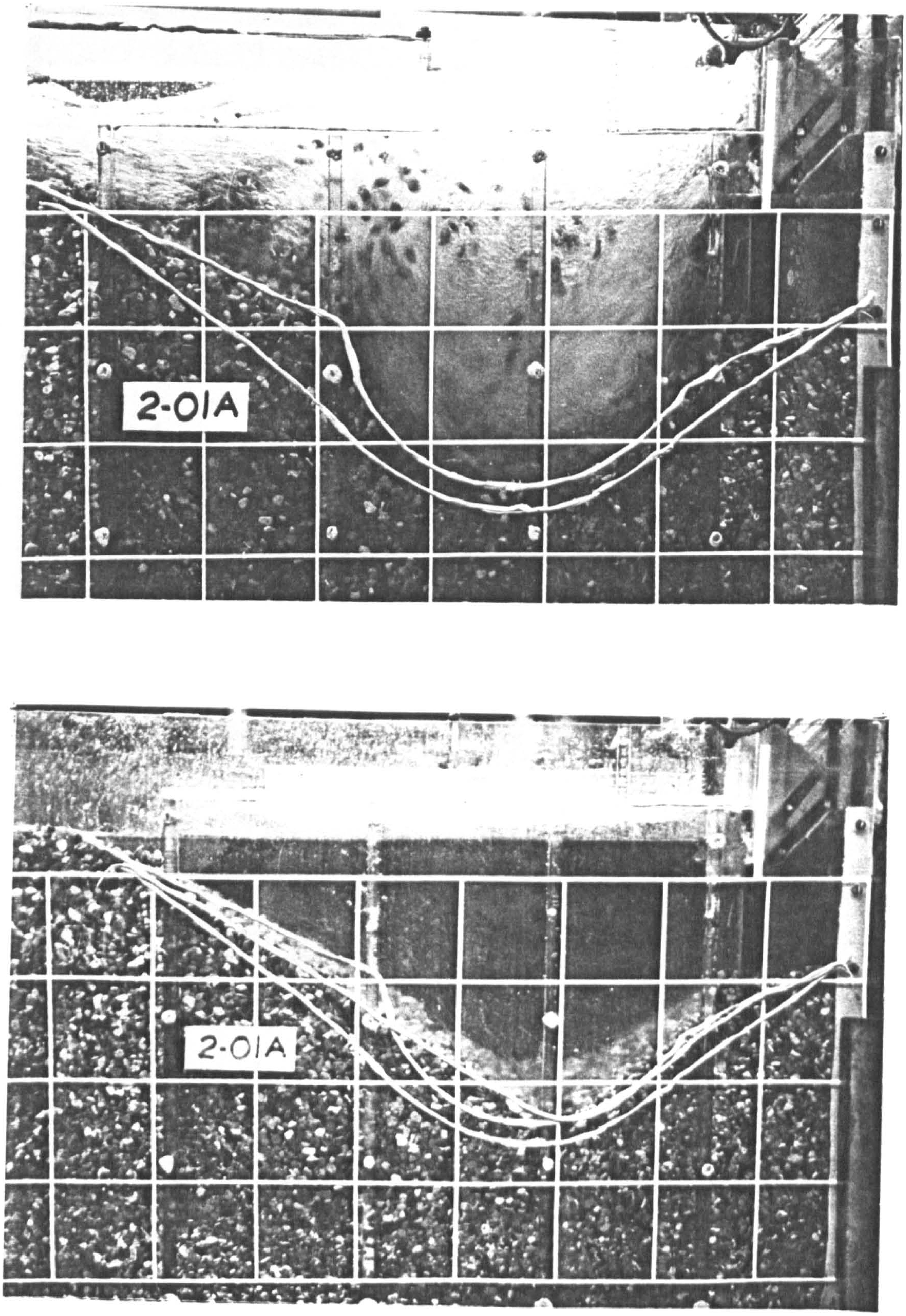
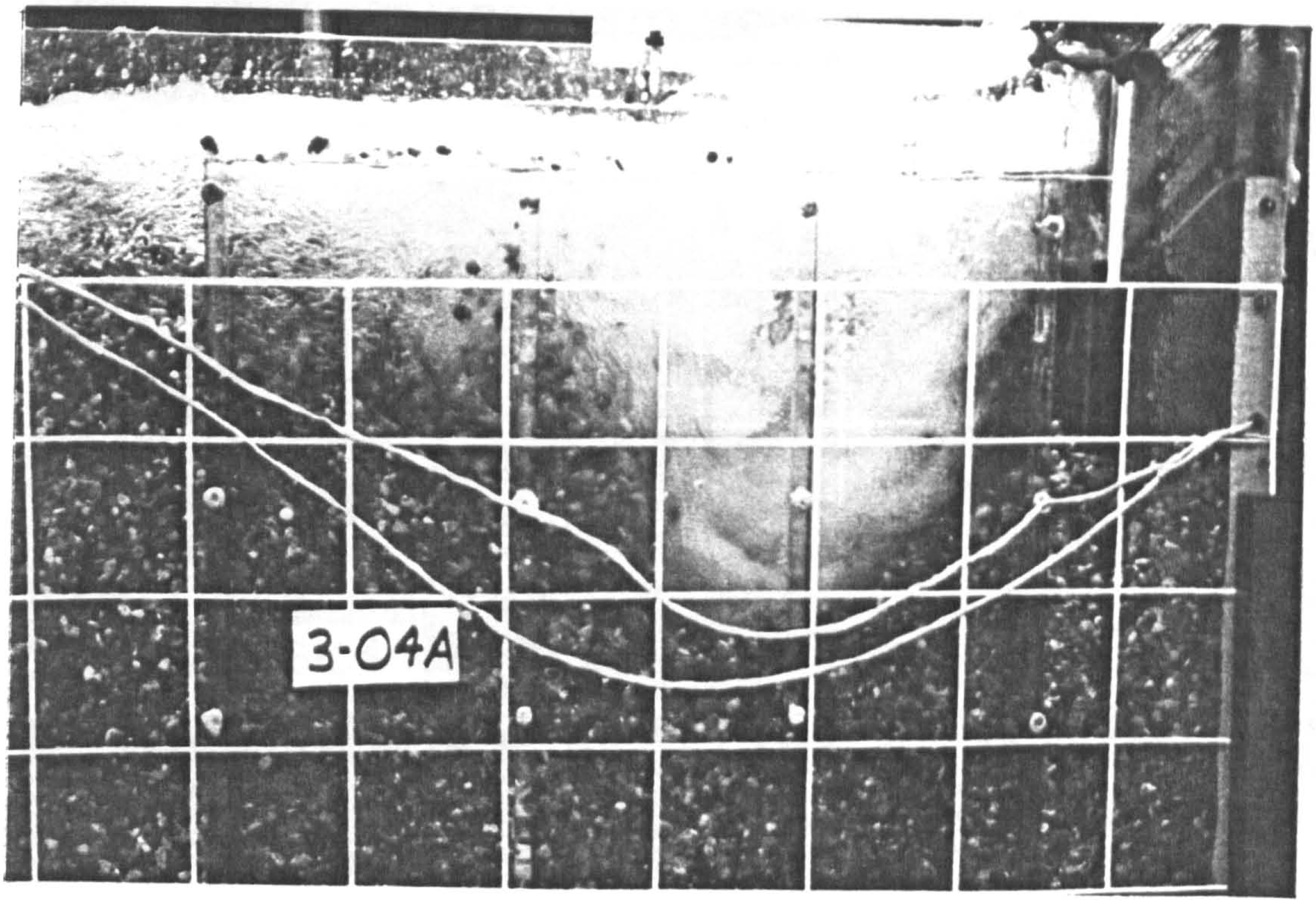


FIGURE 4.13 Scour Results for Test 2-01A (Q=10 l/s, H=0.495m, Air=4.74 l/s).



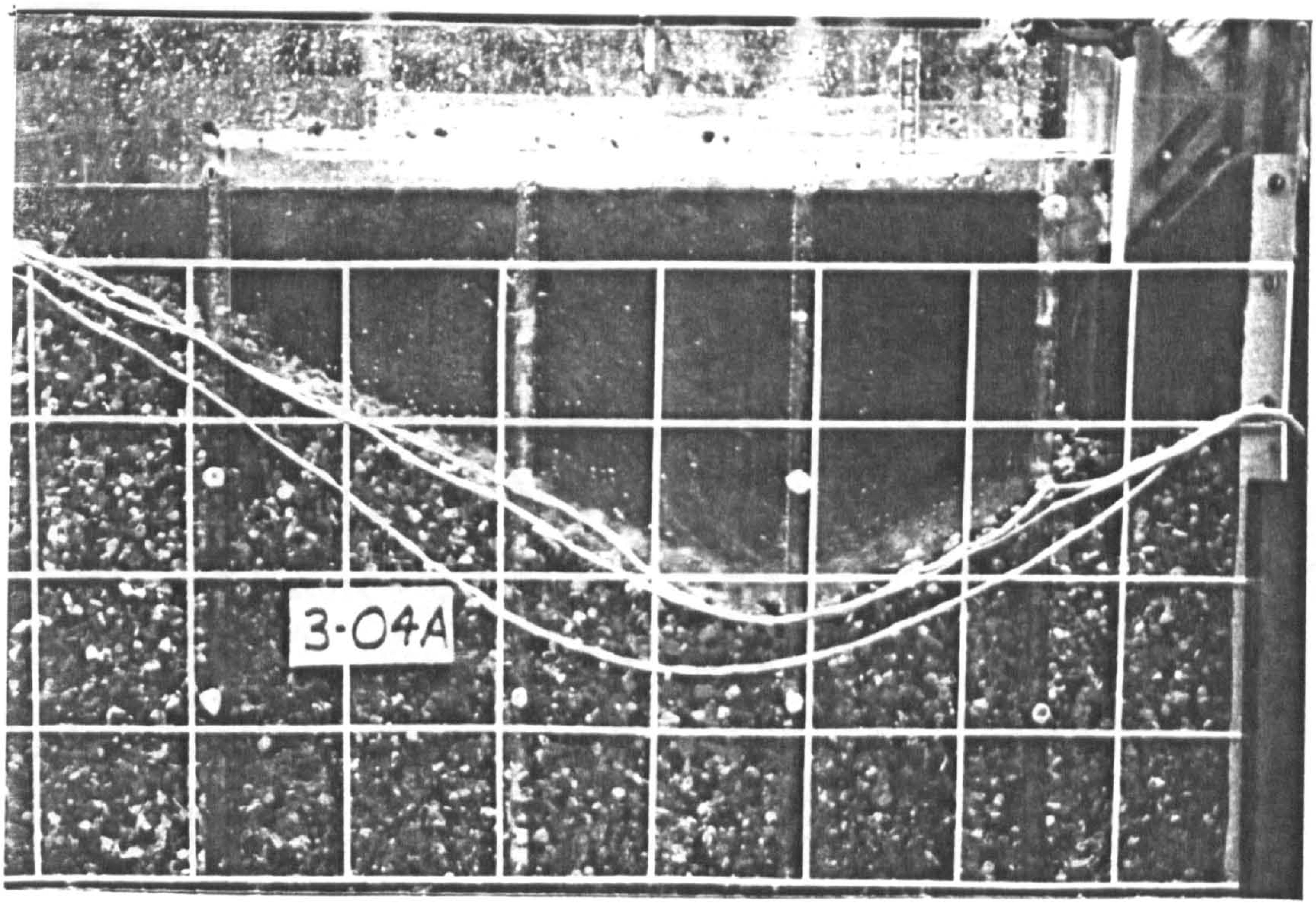
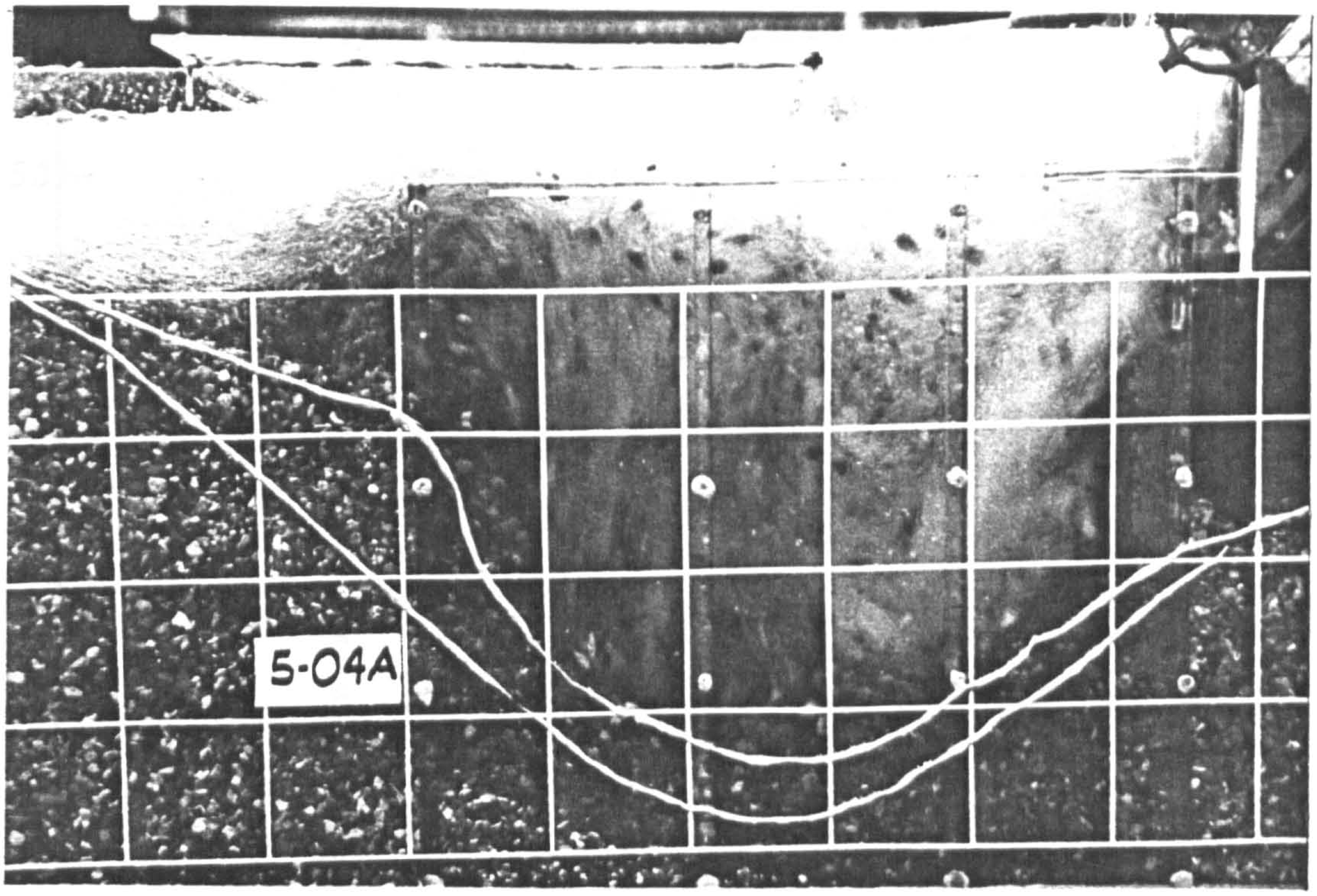


FIGURE 4.14 Scour Results for Test 3-04A (Q=7.5 l/s, H=1.250m, Air=8.95 l/s).



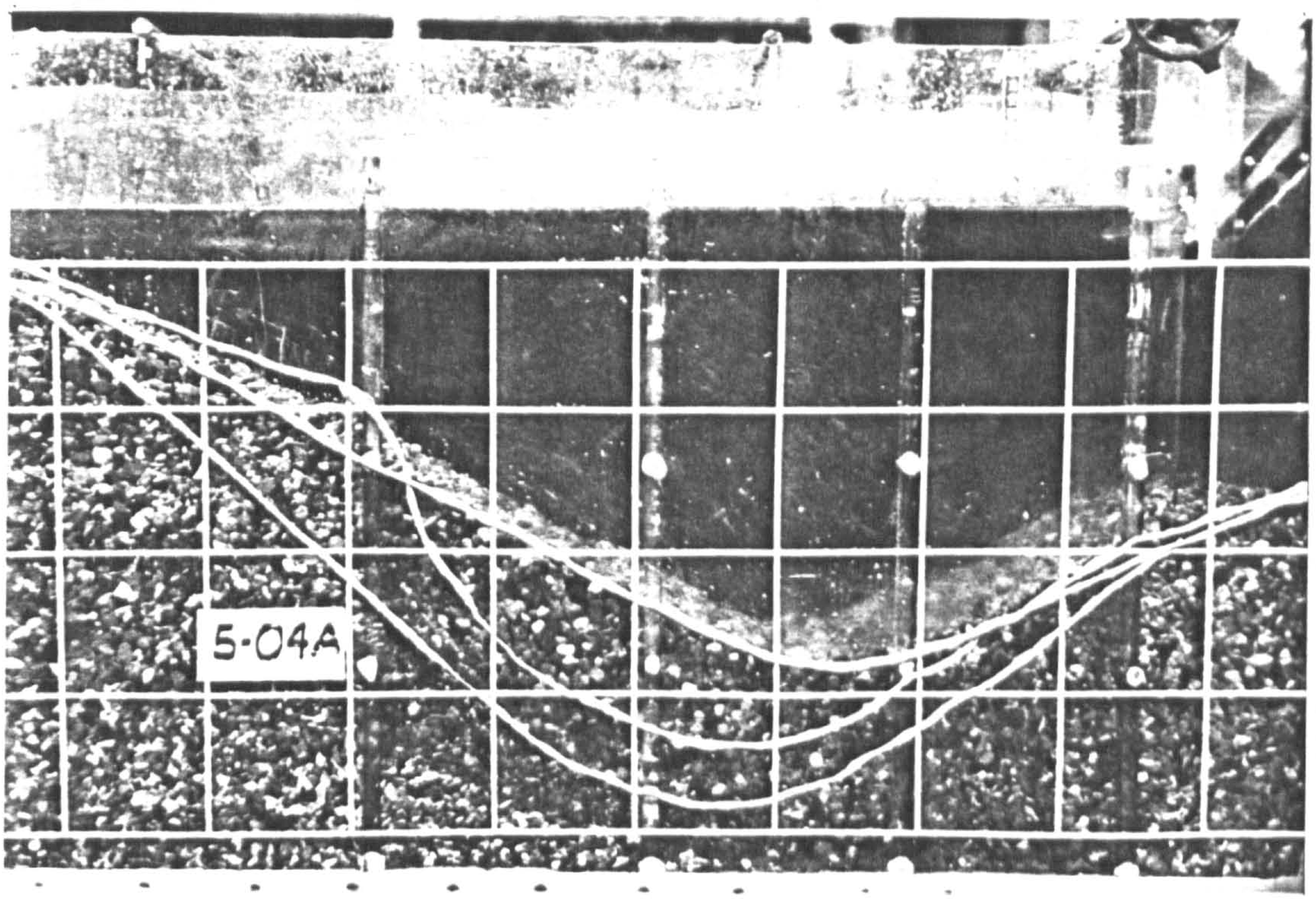
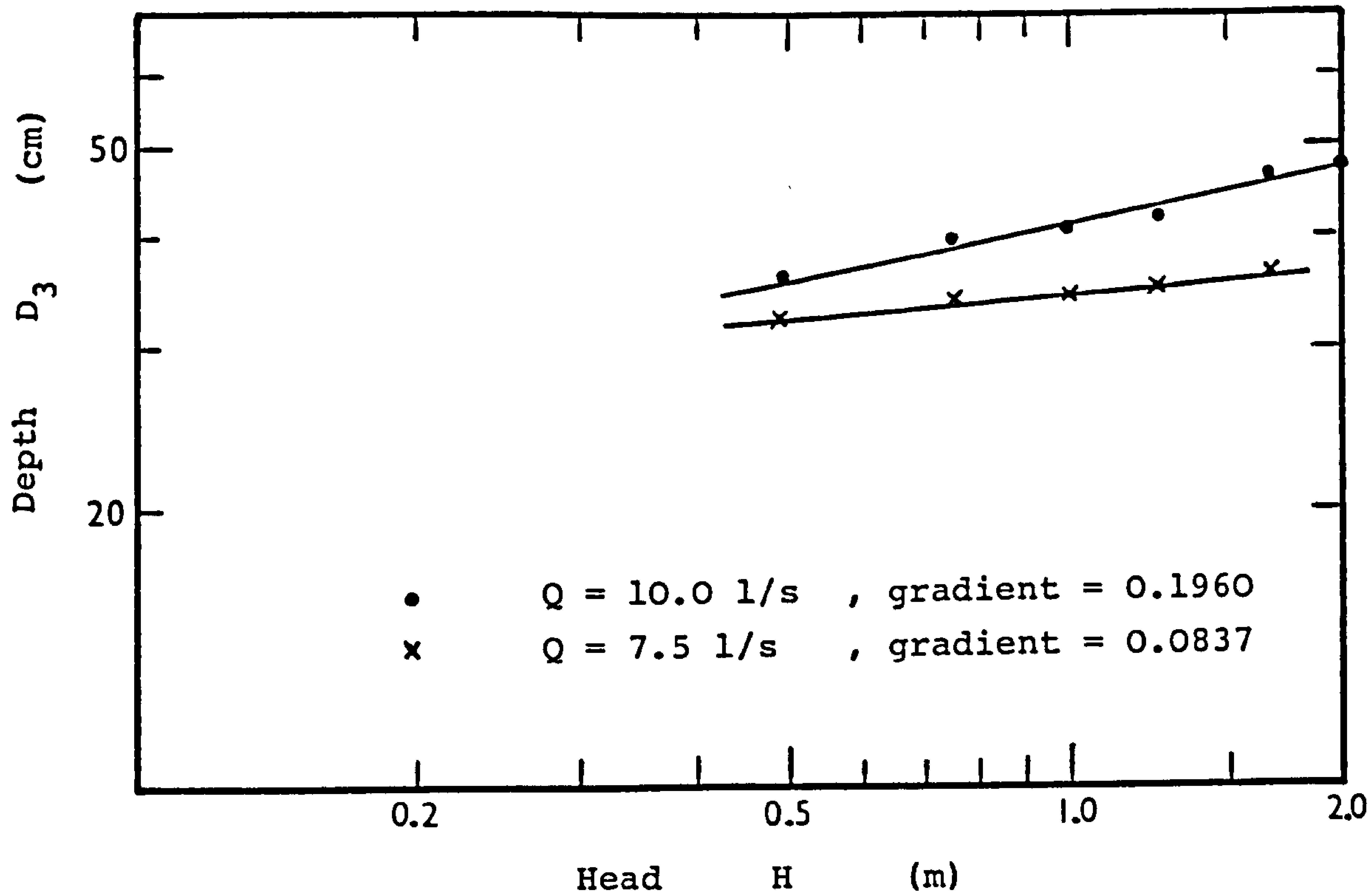


FIGURE 4.15 Scour Results for Test 5-04A (Q=10.0 l/s, H=2.010m, Air=15.23 l/s).



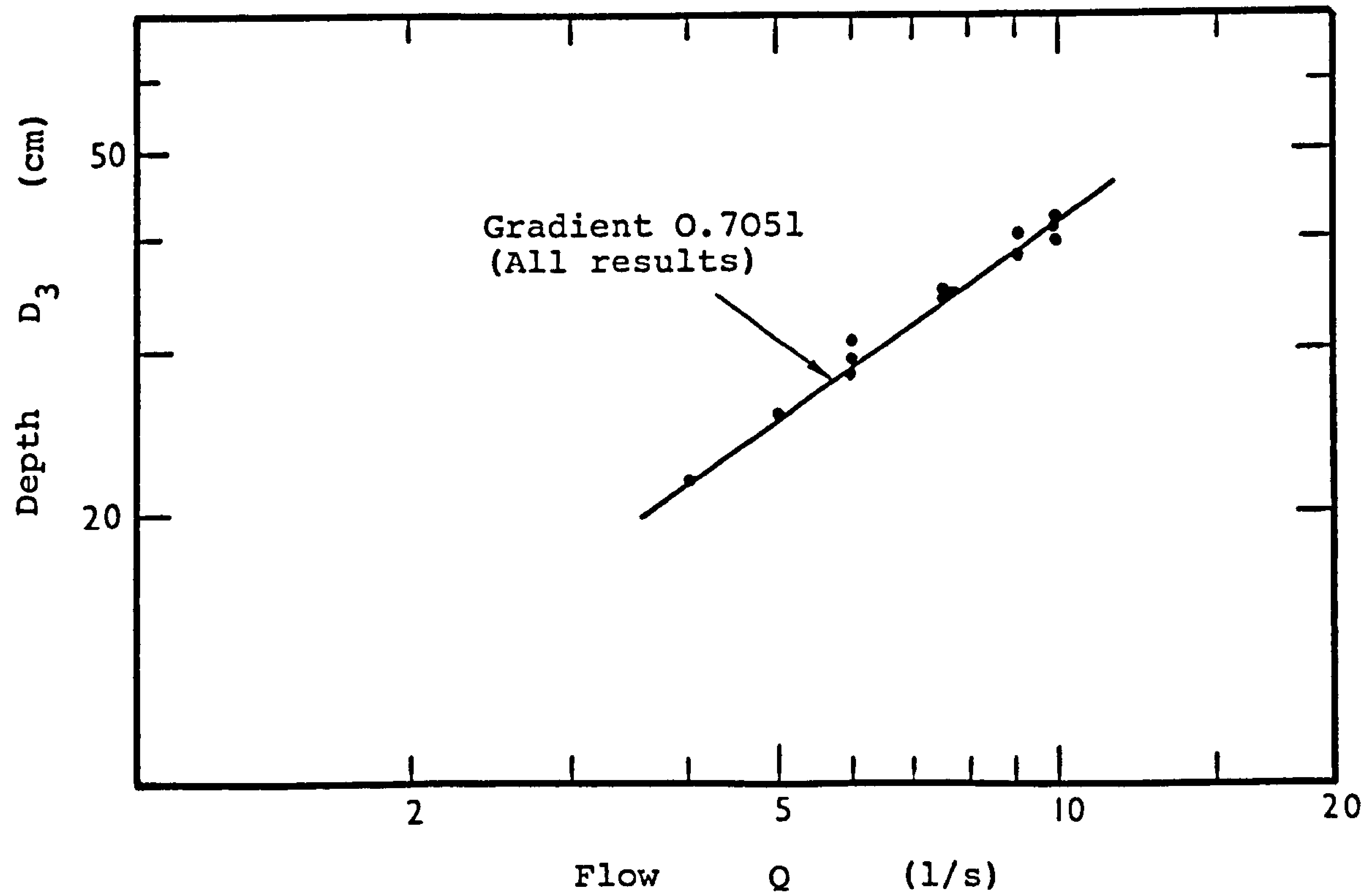


FIGURE 4.16 Variation of Scour Depth, D_3, with Flow and Head Drop for Aerated Flows.

Flow (l/s)	Head Range	No. of Results	Scour Depth	Gradient of Correlation	Coeff. of Correlation
7.5	49 -165	5	D_1	0.1103	0.9623
7.5	49 -165	5	D_2	0.0340	0.6043
7.5	49 -165	5	D_3	0.0837	0.9856
10.0	49.5-201	6	D_1	0.0766	0.8429
10.0	49.5-201	6	D_2	0.1611	0.9426
10.0	49.5-201	6	D_3	0.1960	0.9800
		Mean Gradient		0.1103	

Correlation of Scour Depth against Head Drop (H)

Flow (l/s)	Head Range* (cm)	No. of Results	Scour Depth	Gradient of Correlation	Coeff. of Correlation
4-10	49 - 201	18	D_1	0.5914	0.9632
4-10	49 - 201	18	D_2	0.7113	0.9634
4-10	49 - 201	18	D_3	0.7051	0.9518
		Mean Gradient		0.6693	

Correlation of Scour Depth against Flow (Q)

(*All cases were used irrespective of (H), this follows the procedure of Table 4.1 although it is accepted that in this case (H) does also have a noticeable effect).

TABLE 4.2 Correlation of Aerated Scour Depths against Head Drop (H) and Flow (Q).

values for x would vary from approximately 0.6 to 0.7 while values for y would vary from approximately 0.03 to 0.2. it can be seen from Table 1.1 in Chapter 1 that these values are much nearer those commonly proposed in scour formulae of the type given above. It can be seen also from Table 1.1 that there is generally a wider variation in values for y than for values of x.

It can only be assumed that the natural entrainment of air by jets plunging into water is a significant factor in producing these values.

Two final series of two dimensional scour tests were carried out, to study the effects of artificially high and artificially low amounts of entrained air and to study variations in tailwater depth. These are discussed briefly below.

4.5 Ultimate Depth Testing with Modified Air Entrainment

On the basis that entrained air seemed to be a significant factor in determining ultimate scour depth, it was decided to extend the range of air to water ratios above and below the range already covered. As mentioned in the previous section, the range covered included air/water ratios from 0.474 to 1.567. In this series of tests, ratios of 0.35 and 0.40 were used to extend the range downwards and a series of tests with ratios from 2.0 to 5.0 to extend the range upwards. The results are given in Appendix A as tests with the Prefix AA. The number in each case represents the percentage air assuming the percentage of water to be 100. Thus the test with an air/water ratio of 0.40 is designated AA-40 and the test with an air/water ratio of 3.5 is designated AA - 350, and so on.

The results were used to supplement the analyses of the overall test results as discussed in Chapter 5. One comment which will be made here concerns the noticeable change in appearance of the flow at air/water ratios above about 2. In these cases the mixture appeared very much as a highly aerated foam to the extent that it became difficult to determine the top level of the water in the 'plunge pool'.

4.6 Tests with Varying Tailwater

It was noted in Section 1.4 of Chapter 1 that scour depth seems to be affected by the depth of tailwater and the inclusion of tailwater depth as a factor can enhance the accuracy of scour depth prediction formulae. In Section 1.4 an optimum value for the effect of tailwater was derived by trial and error against an existing body of model data, assembled in a previous work by the writer (Mason 1983). This value was found to be tailwater depth (h) raised to the power 0.15.

It was decided to check this figure using the scour apparatus by choosing a typical flow and head drop and carrying out scour depth tests over a range of tailwater depths. It was also decided to exclude entrained air in case this further variable affected the results.

Scour test 3-03 was chosen as the base test to work from. This had a flow of 7.5 l/s, a head drop (H) of 1 m and a bed level 70 mm below datum. Additional tests were carried out with the same head drop and flow but with initial bed-below-datum depths of 125, 170, 225 and 270 mm. The results are presented in Appendix A under the designations 303-125, 303-170 etc. etc. They are presented graphically in Figure 4.17.

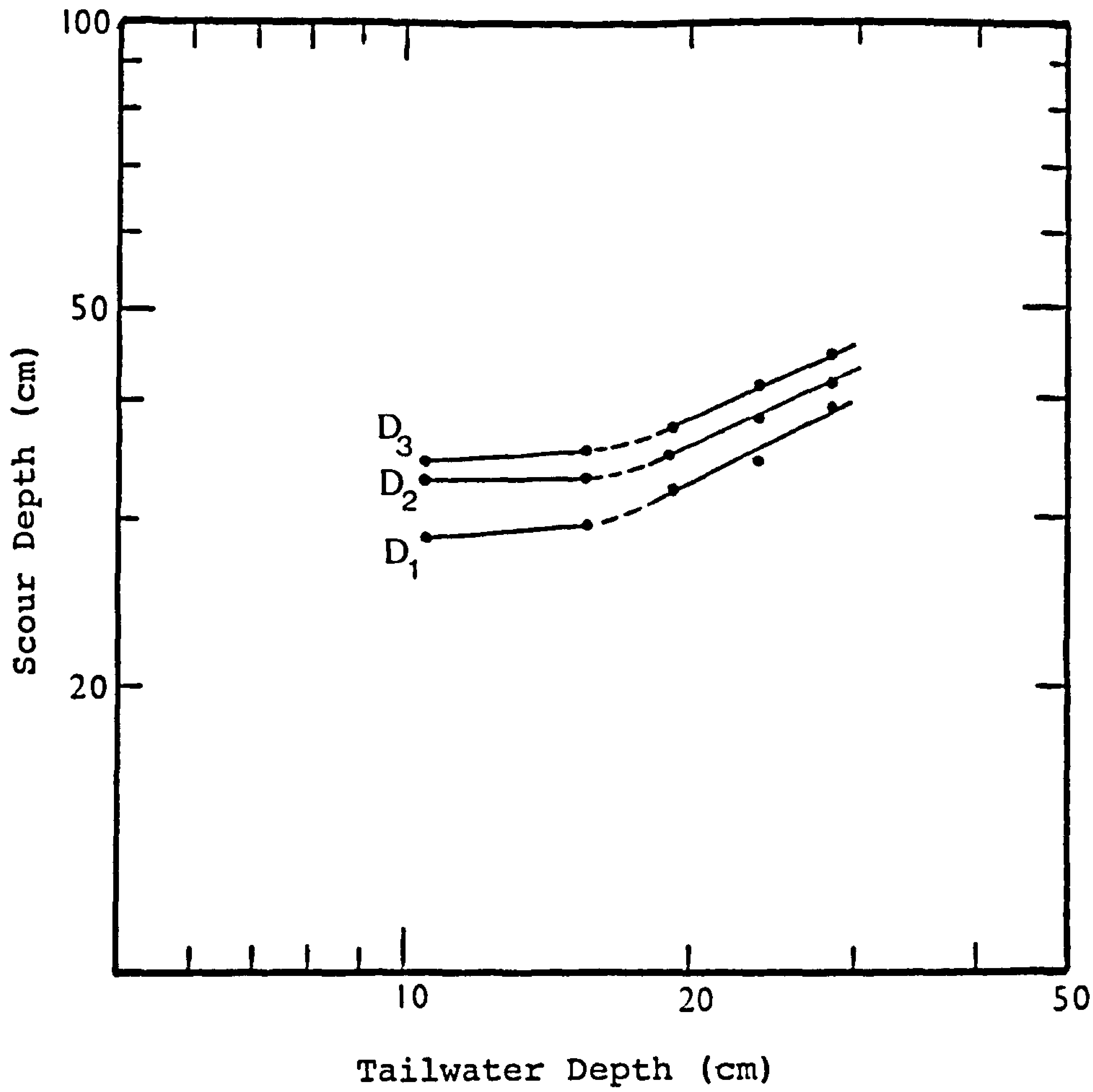
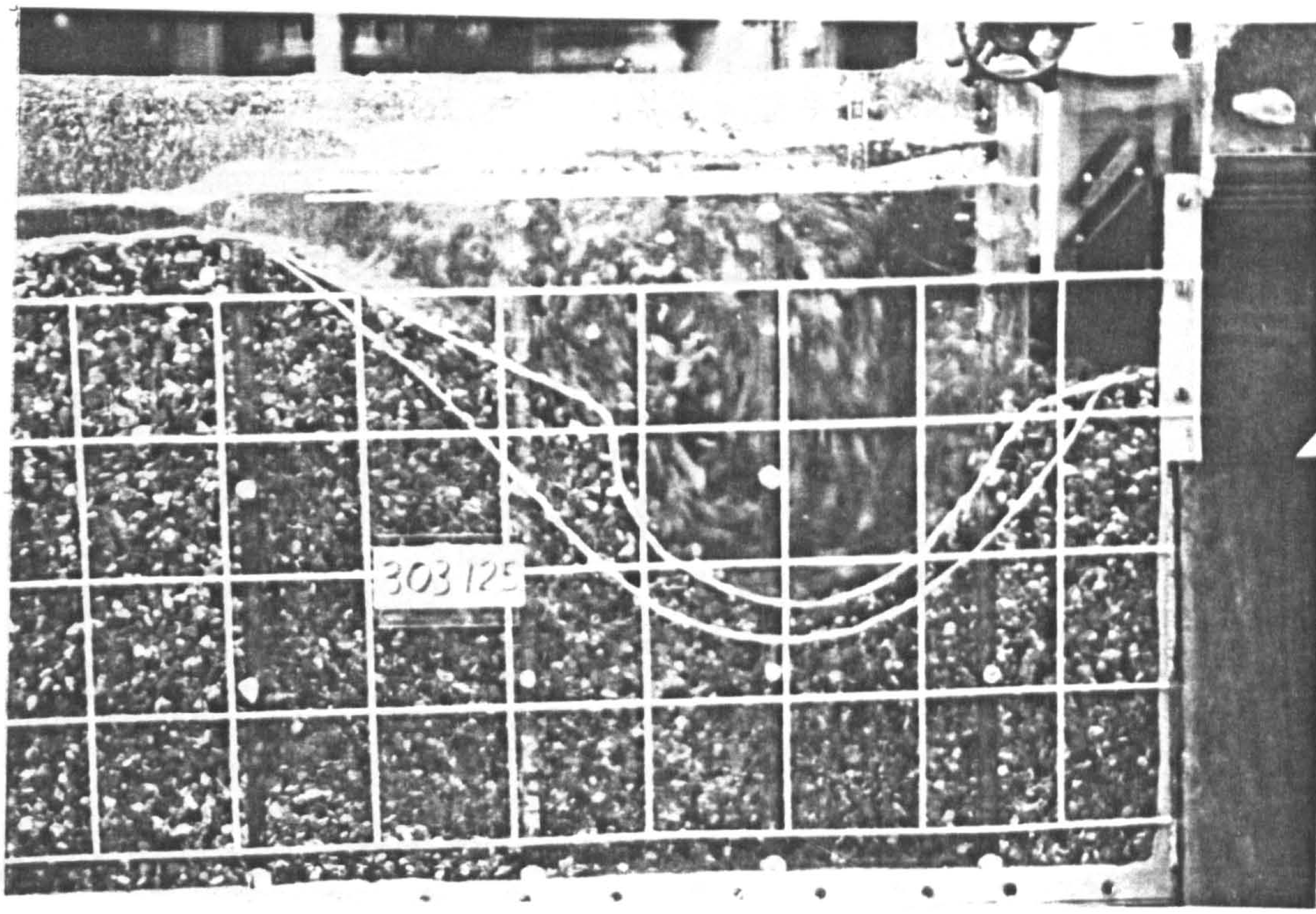


FIGURE 4.17 Variation of Scour with Tailwater Depth.



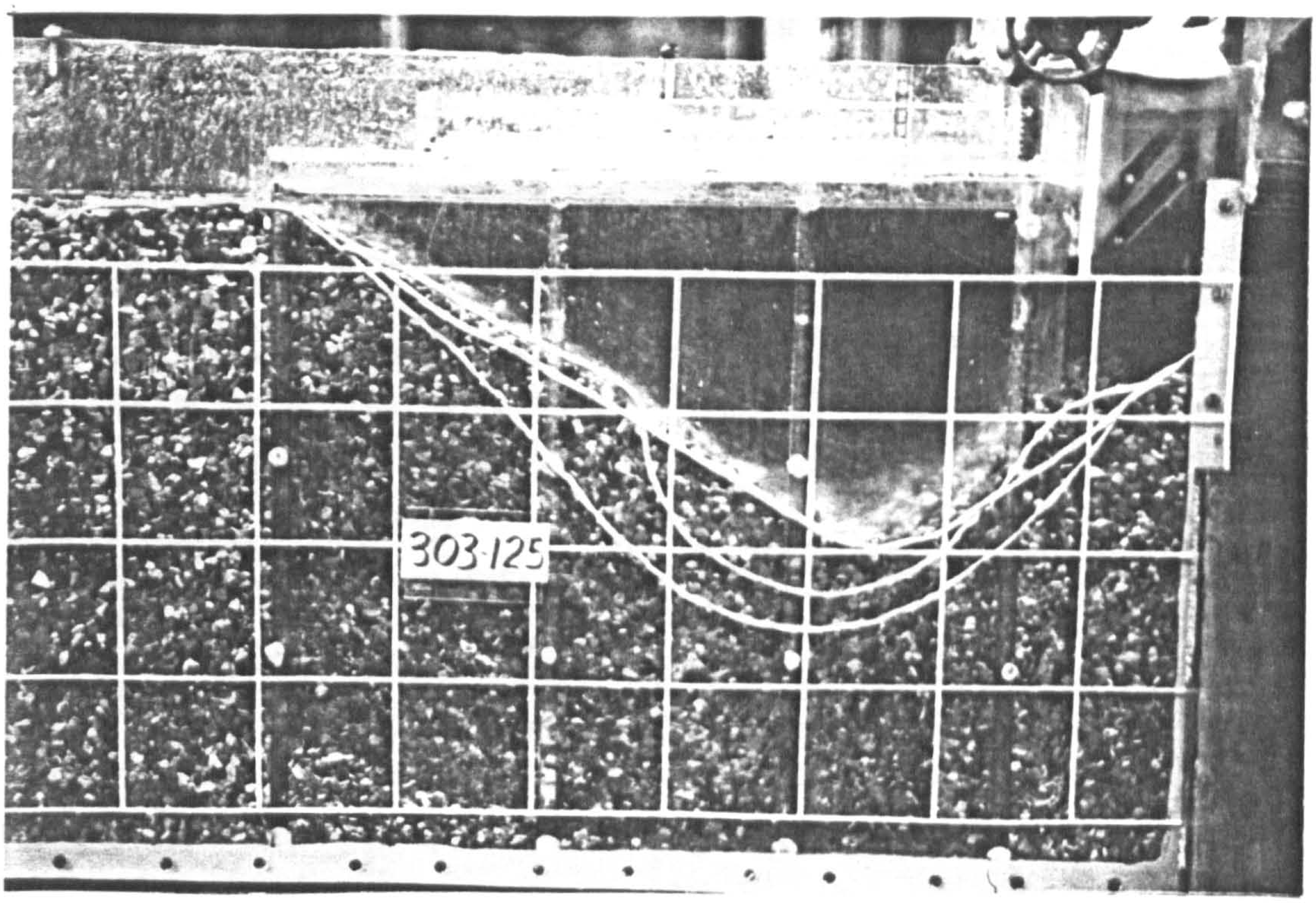
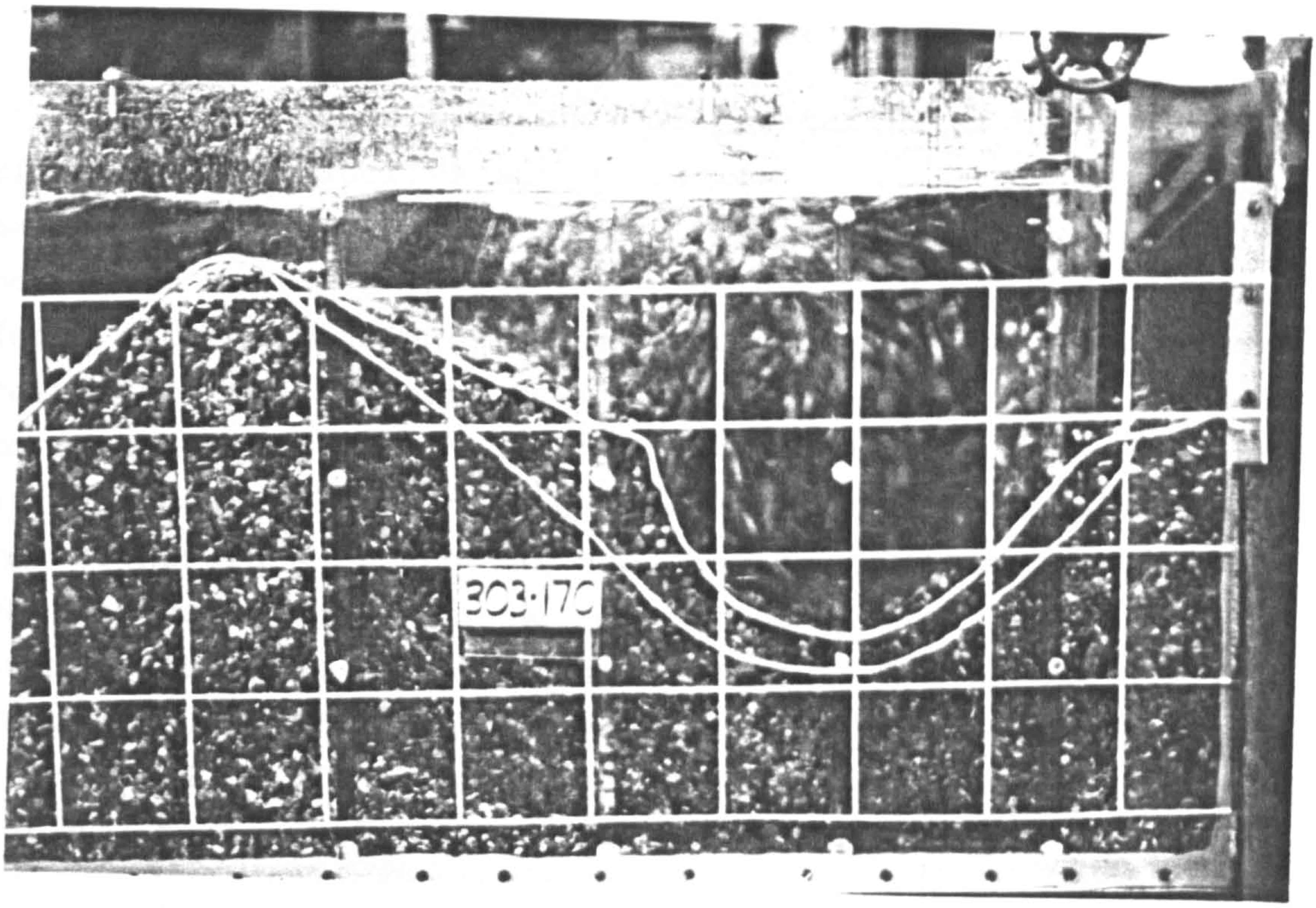


FIGURE 4.18 Scour Results for Test 303-125 (Q=7.5 l/s, H=1.000m, Tailwater Depth 125mm).



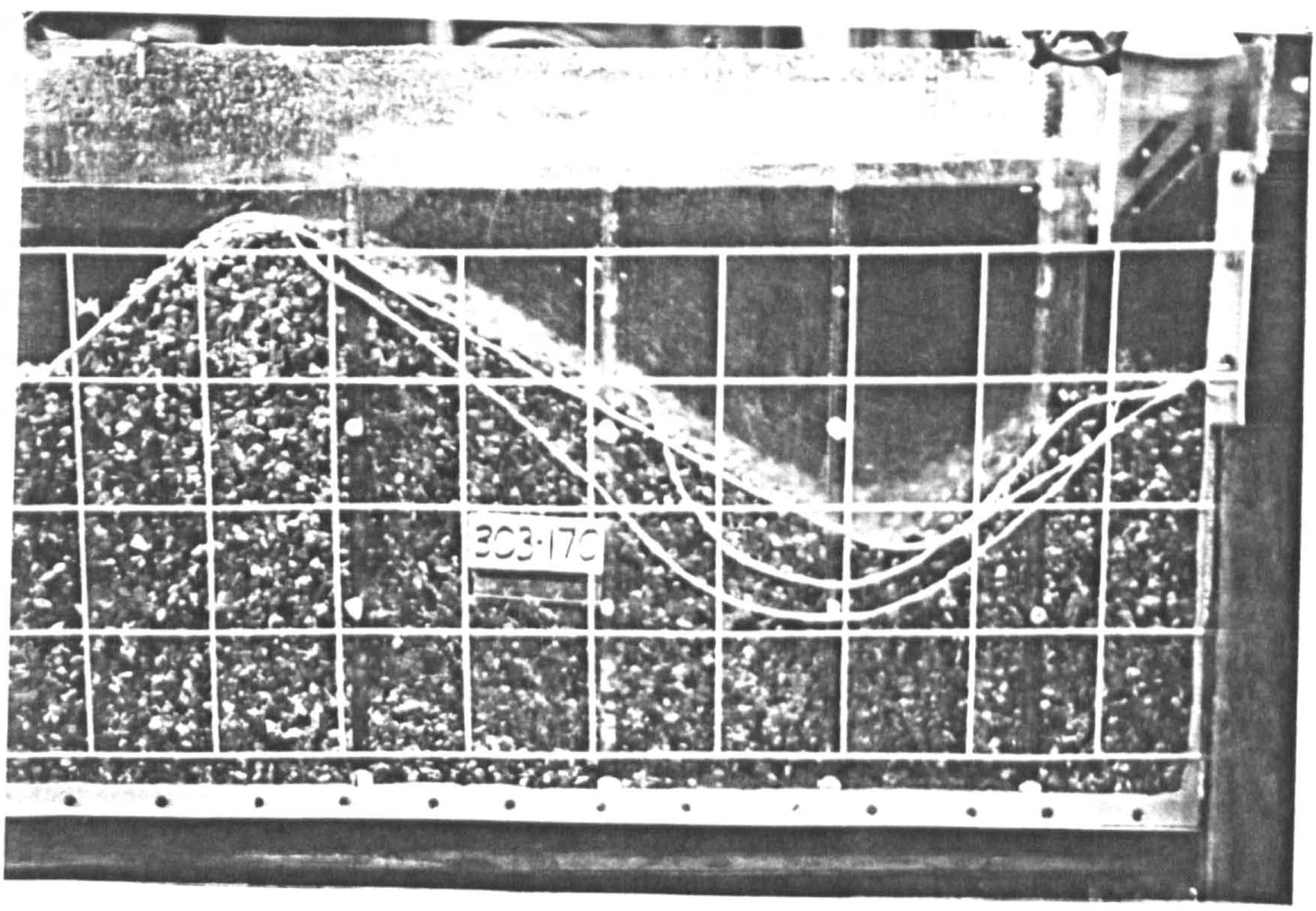


FIGURE 4.19 Scour Results for Test 303-170 (Q=7.5 l/s, H=1.000m, Tailwater Depth 170mm).

It can be seen that at low tailwater depths the effect of tailwater variation is low. In a scour depth expression, the exponent to which tailwater depth (h) would be raised would be in the order of 0.05. As the tailwater depth increases so does its effect on scour with an exponent value for (h) of around 0.40 at high tailwaters. This change corresponded to two distinct modes of bar formation downstream of the scour hole. At high tailwaters the bar grew higher and higher in a triangular mound as scour progressed. In shallow tailwaters, as the mound reached near the water surface it began to extend downstream in a long flat profile. Compare the difference in mound profiles depicted on Figures 4.18 and 4.19. The tests depicted bridge the transition range between high and low exponent values for h.

It would appear that the effect of tailwater depth could itself be a variable, but clearly the value of 0.15 for the exponent of (h) derived earlier is not unreasonable as a typical value.

The tests on tailwater variation were performed out of interest and it is not intended to pursue the results in any further detail in this work. It is considered that other considerations such as air entrainment are the principle object and discussion of the overall test results, with this in mind, is carried out in Chapter 5.

CHAPTER 5

INTERPRETATION OF TEST RESULTS AND COMPARATIVE STUDIES

5.1 Scour Depths due to Non-Aerated Flows

Perhaps the first insight into interpreting the scour test results presented in Chapter 4 may be gained by considering the non-aerated scour results. The equation obtained was:

$$D = K\,q \qquad \ldots\ldots \quad (5.1)$$

The implications of this result becomes apparent if one considers them in conjunction with Figure 4.2 in Chapter 4. For any given scour regime there will be a pattern of flows and return currents within the scour hole and these will all have finite thicknesses. Assuming that the patterns of scour and flow stay the same as scour depths change it can be seen that the thicknesses of internal currents must also be changing directly with flow. If scour depth D doubles then the thicknesses of all the internal currents also doubles. If also, as implied by equation 5.1, flow doubles, then velocities will stay the same. In fact, the direct implication of equation 5.1 is that for a given pattern of flows within a scour hole, as q changes, velocities remain constant.

Conversely expression 5.1 could be derived from the assumption that velocities remain constant as q and D vary. If one considers a cross section through the scour hole shown in Figure 4.2, then the thickness of any internal flow or return current will be directly proportional to overall scour depth D. The velocity of any given internal current will be:

$$v = \frac{q}{kD} \qquad \ldots\ldots\ldots \quad (5.2)$$

If v is also a constant which we now amalgamate with the constant k to form a new constant K, then:

$$D = K q \qquad \text{.........} \quad (5.3)$$

The above analyses do not define which particular velocity within the scour hole is critical in governing when scour has stabilized. Whether it is the velocity initiating scour at (A), see Figure 4.2 or the ones at (D) and (F) which affect bar formation. Probably it is a combination or interaction of various velocities.

If one considers further the implications of constant velocity at stable scour conditions, one conclusion that can be drawn is that it is in fact the force on the particles which is the factor actually governing scour. When particle size, shape and density and water density remain constant, then a characteristic force can be replaced or represented by a characteristic velocity. The concept of constant force rather than constant velocity does, however, enable us to interprete the effects of flow aeration.

5.2 Scour Depths due to Aerated Flows

The force on a particle due to a moving fluid can be expressed as:

$$F = Cd \ A \ \rho \ v^2 \qquad \text{........} \quad (5.4)$$

where F = force on the particle
Cd = particle shape coefficient
A = particle cross sectional area
ρ = fluid density
v = fluid velocity

If we use the suffice, w, to denote non-aerated flow and the suffix a, to denote aerated flow, then if:

$$\rho w = 1.0$$

then $$\rho a = \frac{1}{(1+\beta)}$$

and from equation 5.2 if:

$$Vw = \frac{q}{k \ Dw} \qquad \text{........} \ (5.5)$$

$$Va = \frac{q}{k_1 \, Da}(1 + \beta) \qquad \text{........} \ (5.6)$$

when β = air/water ratio

and q = unit water flow in both cases

It will be noticed that the aerated flow velocity is enhanced by the additional fluid (air) added to the flow in the scour hole.

From equation 5.4, the force on the particles in the case of non-aerated flow can be characterised by the expression:

$$Fw = Cd \, . \, A. \ 1 \, . \, \frac{q^2}{K^2 Dw^2} \qquad \text{.......} \ (5.7)$$

The equivalent force on the particles in the case of aerated flow would be:

$$Fa = Cd.A. \frac{1}{(1 + \beta)} \cdot \frac{q^2}{K_1^2 \ Da^2} (1 + \beta)^2 \text{...} \ (5.8)$$

If at ultimate scour conditions the characteristic forces on the particles are the same in both cases, then $Fw = Fa$. Equations 5.7 and 5.8 can be made equal and after some cancelling produce:

$$\frac{1}{K^2 \ Dw^2} = \frac{1}{K_1{}^2 \ Da^2} (1+\beta)$$

so that

$$\frac{Da}{Dw} = K \ (1+\beta)^{0.5} \qquad \ldots\ldots \ (5.9)$$

This implies that if scour depth Dw (from a non-aerated flow case) is known, the change in scour depth to Da can be calculated purely as a function of air entrainment.

In order to test this, depths D_1 D_2 and D_3 from the series of aerated flow scour tests were compared with the equivalent values from the equivalent non-aerated tests. That is, for example, result D_2 from test 3-01A was compared to result D_2 from test 3-01. In each case the values of Da/Dw for D_1, D_2 and D_3 were plotted against β. The results are shown on Figures 5.1 to 5.3.

Superimposed on the figures is a line representing equation 5.9 and with K = 0.70. This value was assumed as, by inspection, Da/Dw generally tended to unity at around β = 1.0. This value for K may reflect in some way the greater lateral extent of aerated scour or perhaps the greater dispersion of aerated jets under water than non-aerated ones. Ervine (1986_a) has shown that whereas a non-aerated jet will disperse at a side angle of about 1 on 5, aerated jets disperse at side angles nearer to 1 on 4. In the force balance made earlier this would imply a dispersion correction from Dw to Da of 4/5 or 0.8. This is expanded upon below.

Figures 5.1 to 5.3 indicate a reasonable agreement between the data points and the force balance approach expressed by equation 5.9. The agreement is better in the cases of D_2 and D_3 than in the case of D_1. Figure 5.4 is particularly revealing. It repeats Figure 5.3 but gives actual values for the data points in terms of flow Q in litres per second. The results further verify that Da/Dw is a square root function of $(1 + \beta)$ but suggest that the constant K is also a function of flow. This may be because the dispersion correction mentioned above was derived assuming flow eminating from a point, in fact dispersion will eminate from a jet of finite thickness. As jet thickness increases for a given overall jet length the dispersion correction will reduce. The general expression would be:

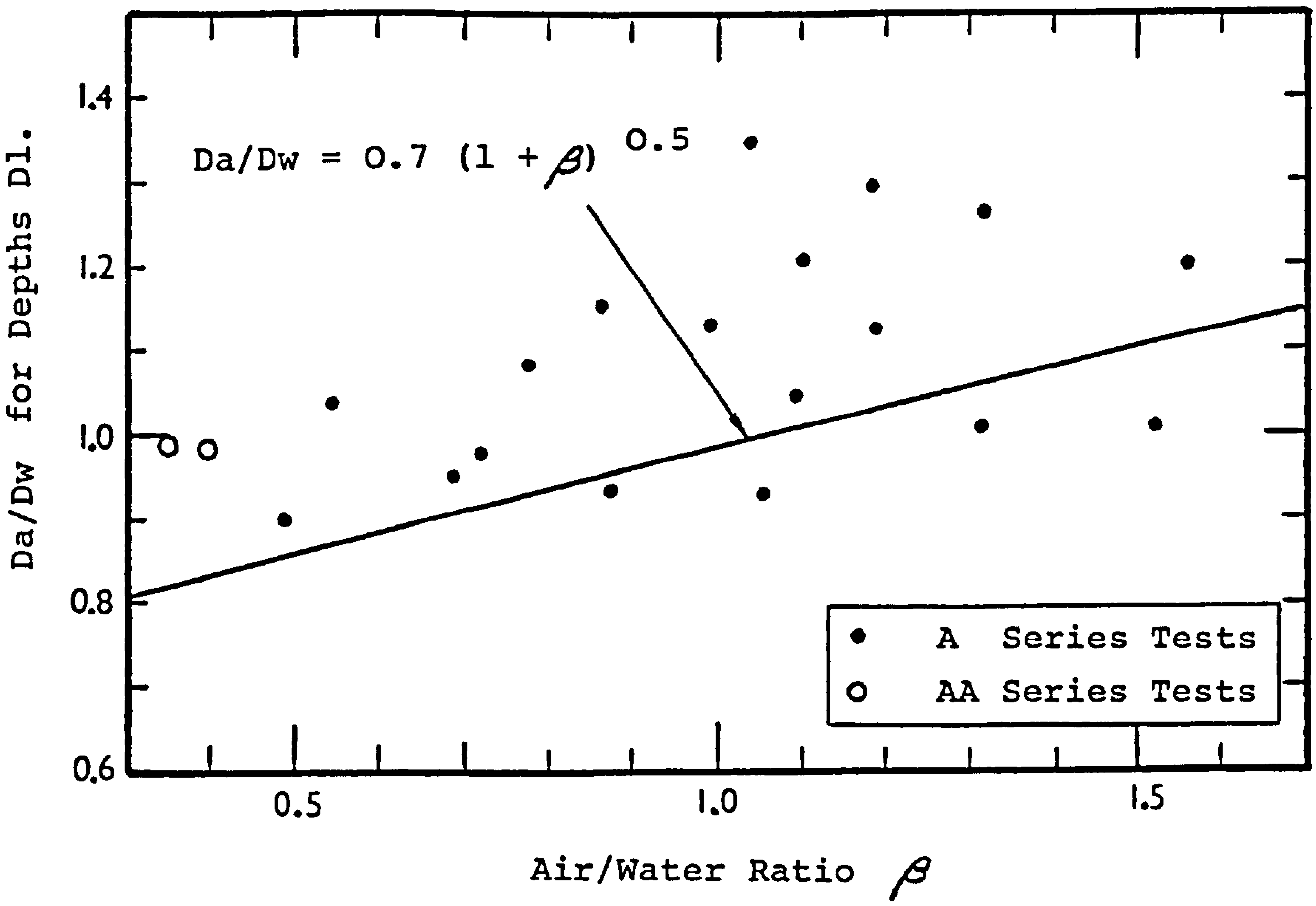
$$K = \frac{(2Lj/0.5 + t)}{(2Lj/0.4 + t)}$$

where Lj = jet length
t = jet thickness

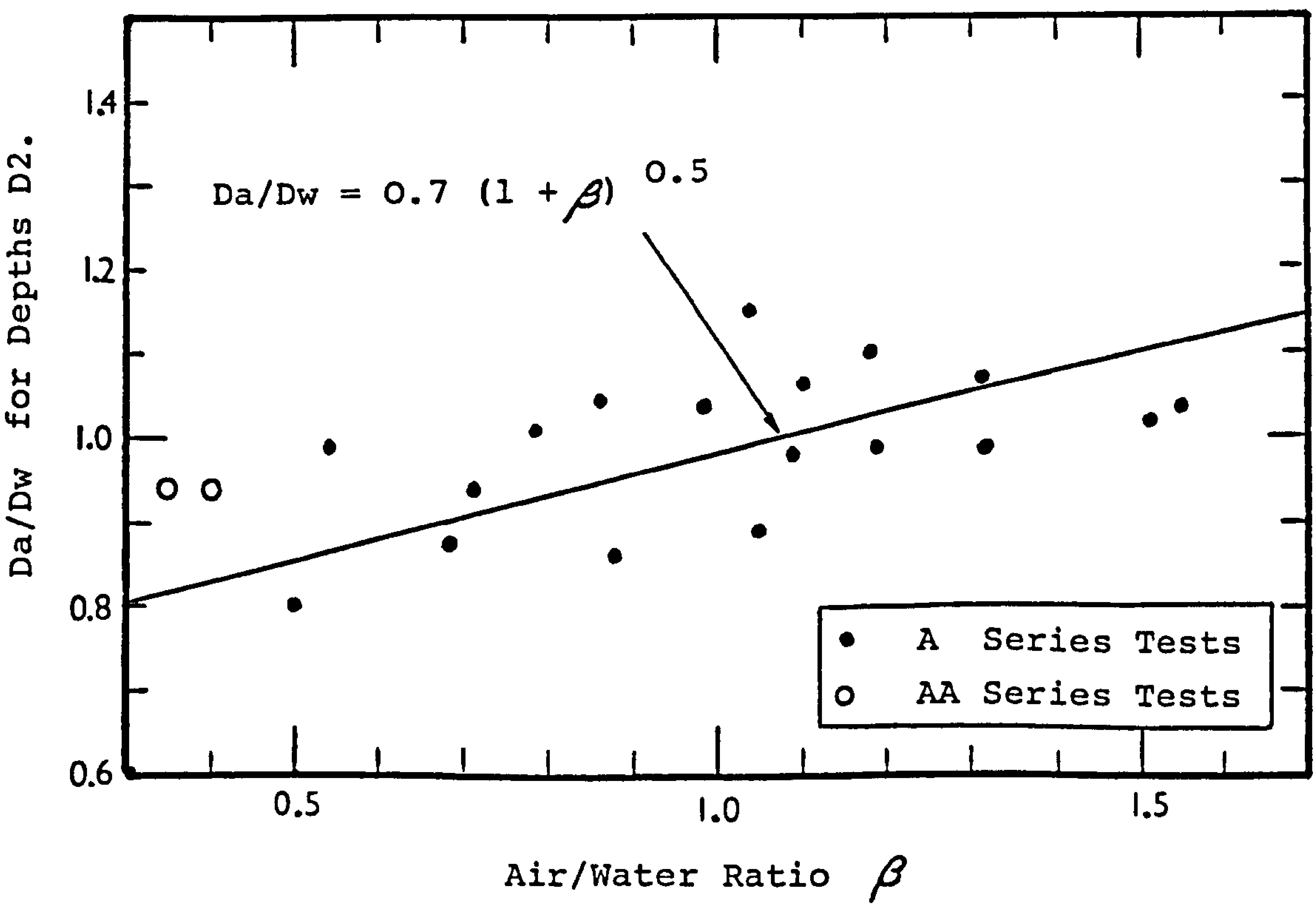
As t tends towards zero

$$K = \frac{(2Lj/0.5)}{(2Lj/0.4)} = 0.8$$

In fact the matter is more complicated still as the dispersion side slopes are not simply 1 on 5 and 1 on 4 but vary before and after the decay length of the inner core of the jet. A detailed discussion of these aspects would be a topic in itself and will not be pursued here other than to discuss the possibilities in general terms. Nor is it considered proven that dispersion of the incoming jet as discussed above is the factor governing the value of K, although the general order of magnitude of the constant derived seems about right and K does appear to reduce as flow (and therefore generally, t increases).



<u>FIGURE 5.1</u> Da/Dw vs. Aeration for Depths D1.



<u>FIGURE 5.2</u> Da/Dw vs, Aeration for Depths D2.

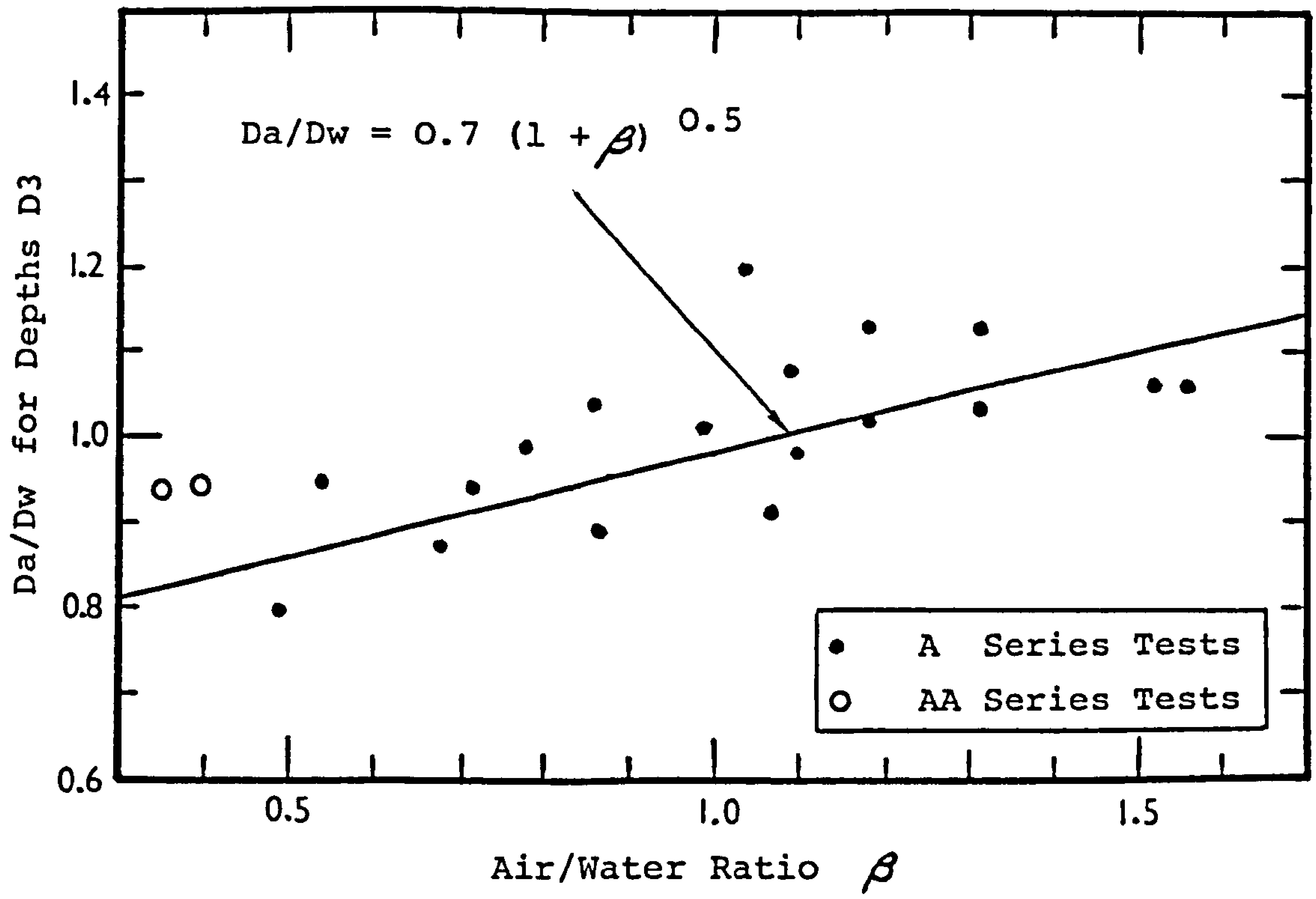


FIGURE 5.3 Da/Dw vs. Aeration for Depths D3.

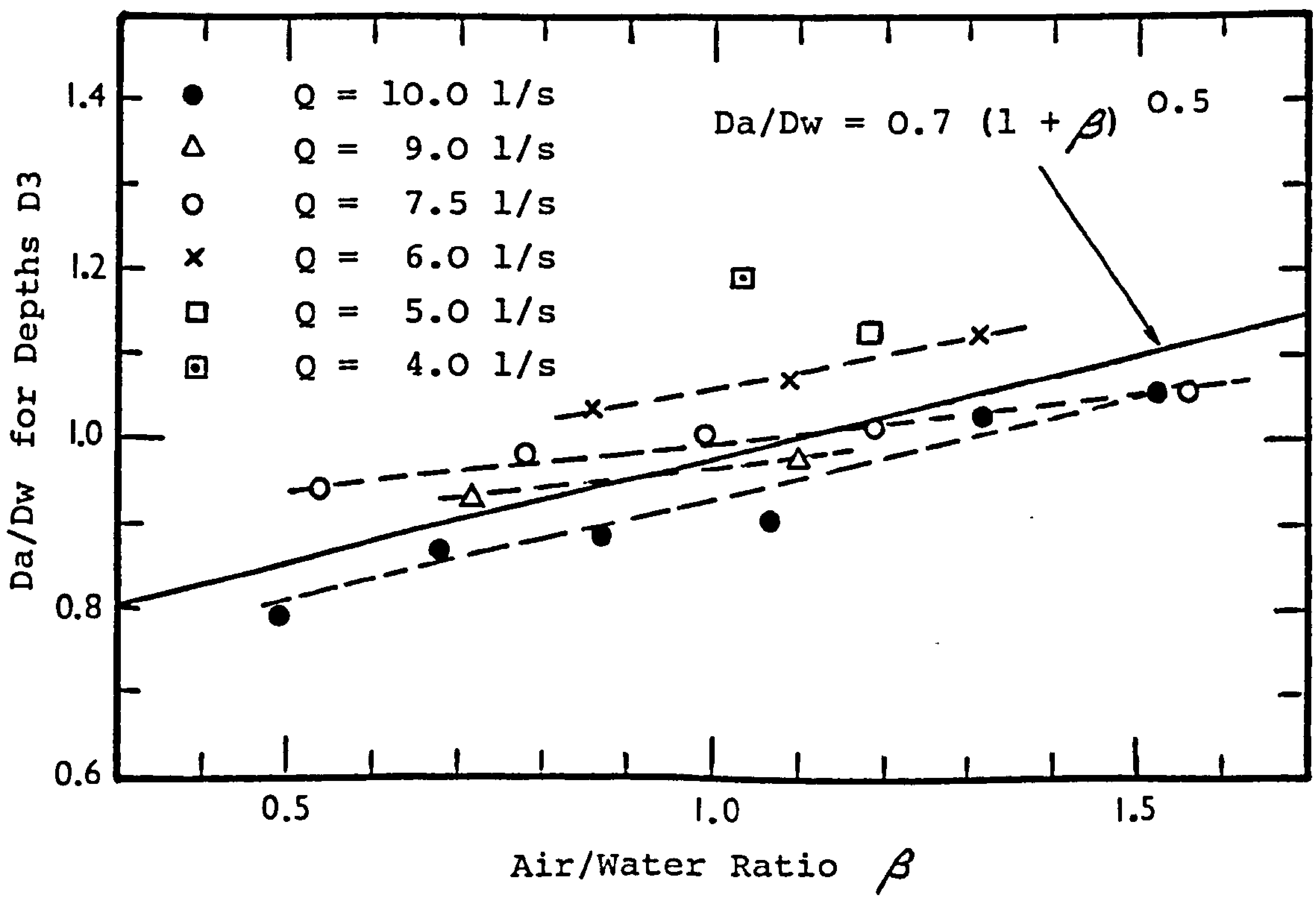


FIGURE 5.4 Da/Dw vs. Aeration for Depth D3 plotted by individual flow.

Lastly two data points can be noted on Figures 5.1 to 5.3 at values of β = 0.35 and 0.40. These were from the AA series of tests where artificially high and low amounts of air were entrained in the flow. The two points shown represent artificially low values and the results are broadly in keeping with the other data points and with the predicted relationship. The artificially high entrained flows had values for β ranging from 2 to 5 and, although not plotted, did not produce values for Da/Dw much greater than about 1.1 and in most cases less. They certainly did not follow the predicted relationship between Da/DW and β. The possible reasons for this are discussed below:

In Section 4.5 of Chapter 4 it was mentioned that there was a noticeable change in the appearance of the flow at air/water ratios above about 2. Ervine was contacted directly by the writer to see if he had any comments on this and in his reply (Ervine, 1987) he made the following observations:

i. He had never measured experimental values of β greater than 3.

ii. If one visualises entrained air bubbles as a mass of spheres, the highest 'packing factor' possible without distortion is a sphere to overall volume ratio of 3 to 4. This gives a sphere volume to remainder volume (i.e. β) of 3.

Clearly from (ii) above, at a value of β equal to 3 the fluid becomes isolated water pockets that are entrained in a matrix of interconnecting air bubbles. It would need very carefully controlled conditions to ensure that the air/water mixture was homogeneous under these conditions. It is not therefore considered by the writer to be surprising that the results obtained from tests using values of β up to about 1.5 do not extrapolate much beyond this range.

This has interesting implications for prototypes. It is generally assumed that air entrainment is significantly more on prototypes than on models. If there is an absolute upper limit on β of 3 with probable effective values being somewhat lower, this may not be the case. This may also go some way towards explaining the apparent fall-off in entrainment rate at high heads and velocities, as reported by Van de Sande and Smith (1973), see Chapter 2, Section 2.3.6.

From the above it is possible to derive a generalised expression for two dimensional scour.

From equation 5.1 and also the results of the non-aerated flow scour tests, it can be shown that for the two dimensional non-aerated case:

$$D = 12\,q \quad \text{(approx)}$$

where D = scour depth in metres

q = unit flow in m^2/s

This can be modified for the aerated case using equation 5.9 with a value for K in equation 5.9 of 0.7 (see Figures 5.1 to 5.4). it would seem reasonable to also modify it for tailwater depth (h) and particle size (d) using exponents of 0.15 and 0.10 respectively, following the findings outlined in Chapter 1, Section 1.4. This gives an overall expression:

$$D = 8.4\,q\,(1 + \beta)^{0.5}\,\frac{h^{0.15}}{d^{0.10}} \qquad \ldots\ldots \text{(5.10)}$$

where $$\beta = 0.2525\,\frac{H^{0.669}}{q^{0.446}}\left(1 - \frac{0.248}{H^{0.50}}\right)$$

(See Chapter 4, Section 4.4)

5.3 The Three Dimensional Scour Case

The derivation of equation 5.10 from equations 5.1 and 5.9 was essentially for two dimensional scour conditions. If the scour hole is able to develop laterally as well as vertically, both equations 5.1 and 5.9 have to be modified. For example if one assumes D is large relative to lateral jet width, W and that the lateral extent of scour stays proportional to D, then in equation 5.2 the characteristic velocity v becomes proportional to q/D^2 rather than q/D. So that

$$v = k \frac{q}{D^2} \qquad \text{......} \quad (5.11)$$

and if the characteristic velocity v is also a constant then:

$$D = K q^{0.5} \qquad \text{......} \quad (5.12)$$

(compare with equation 5.3).

Equations 5.5 and 5.6 would also have to be modified to incorporate D^2 rather than D and this in turn would affect equations 5.7 and 5.8. In both of these D^2 would become D^4. Carrying this through as an equivalent expression to equation 5.9 gives:

$$\frac{Da}{Dw} = K (1 + \beta)^{0.25} \qquad \text{......} \quad (5.13)$$

Thus for the three dimensional scour case the equivalent expression to equation 5.10 would be:

$$D = K q^{0.5} (1 + \beta)^{0.25} \frac{h^{0.15}}{d^{0.10}} \qquad \text{......} \quad (5.14)$$

where β is derived as before.

It is accepted that this is an approximation. A thorough analysis should arguably change equation 5.2 to a function of W and D rather than just D^2. The amount of detail implied by such an expression would not, however, be justifiable without reinforcement from a second series of detailed three dimensional scour testing. It is proposed to leave such testing and detailed analyses to others as a natural progression from this work. The change from D in equation 5.2 to D^2 in equation 5.11 (and hence from q in equation 5.3 to $q^{0.5}$ in equation 5.12) represents a limiting case. The general case could be represented by incorporating a complex function of W and D or approximated to by an intermediate expression for q between q and $q^{0.5}$.

5.4 Comparative Analyses

In order to test the assumptions and conclusions drawn in the Sections above it was decided to test the formulae derived against an alternative set of scour data. The data selected was the model test case histories described in Appendix C of the writer's previous M.Phil Thesis (Mason, 1983), see also Chapter 1, Section 1.3. This data is summarised in Appendix B.

The formulae were used to process this data and calculate scour depths (Dcalc). These were then compared in each case with the actual scour depths obtained (Dact) to obtain an error factor,(Dcalc/Dact). The variation in these error factors then indicated the potential accuracy of the formulae.

Equation 5.10 was the first to be tested. This was derived essentially as a two dimensional scour formula. The result was a mean error factor of 2.4657 and a coefficient of variation of the factors of 42.2193%. This rather poor result can be better understood if one views the individual error factors plotted against W/D, see Figure 5.5. It can be seen that the scatter of results tends to decrease as W dominates D, in other words as two dimensional

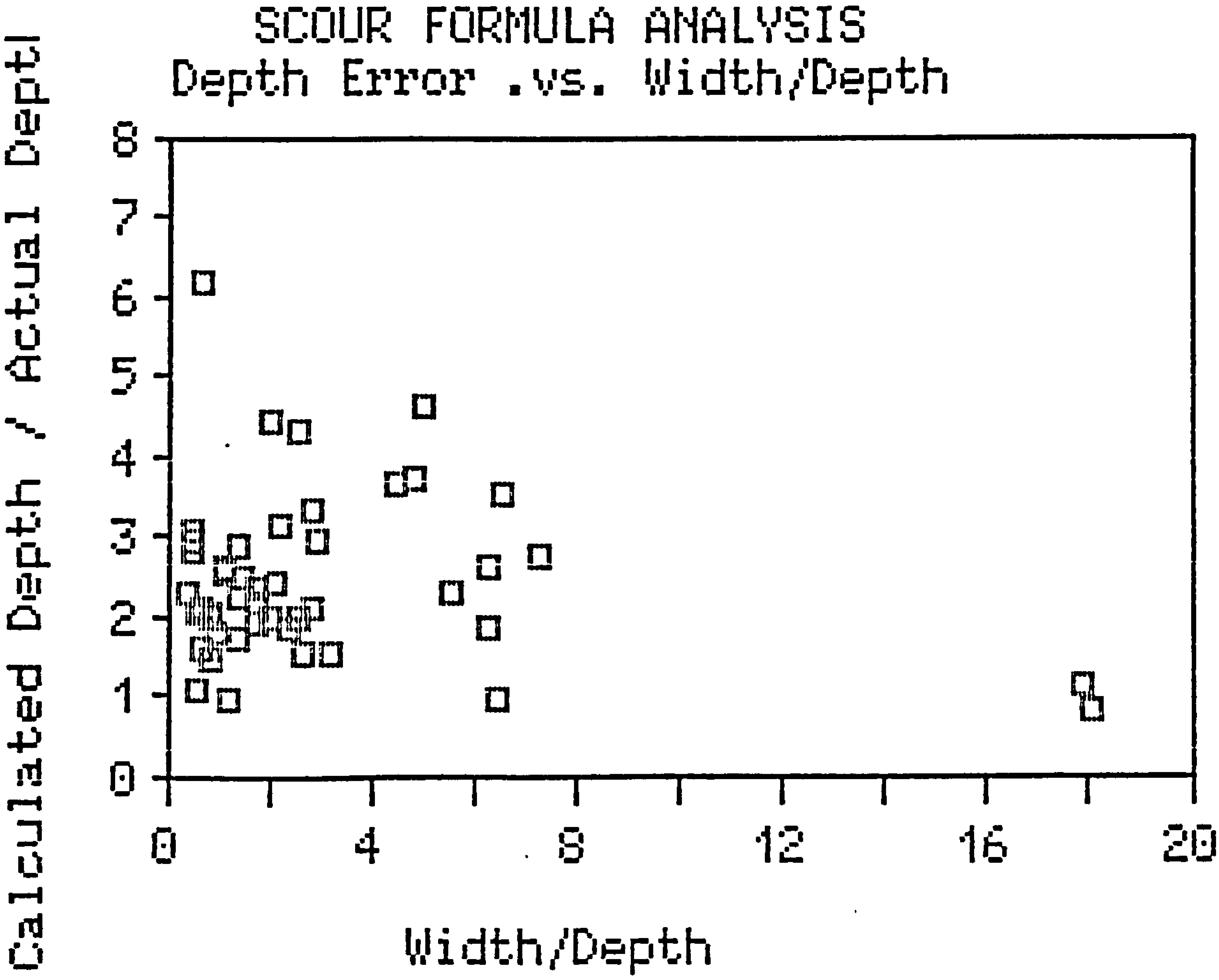


FIGURE 5.5 Depth Error Factors from Two Dimensional Equation 5.10 vs. W/D.

conditions are approximated to. At a value of W/D equal to 18 the error factors on the two data cases shown are approximately unity.

In order to test the assumptions made in Section 3 above, the exponents of q and $(1 + \beta)$ were changed in turn to assess their effect on accuracy. In effect equation 5.10 was progressively changed to equation 5.14.

Changing q to $q^{0.50}$ reduced the coefficient of variation of the error factors from 42.2193% to 29.3045%.

Changing $(1 + \beta)^{0.50}$ to $(1 + \beta)^{0.25}$ reduced the coefficient of variation of the error factors further to 27.9418. Finally the exponent of q was set at an intermediate value of 0.6 (see discussion at the end of Section 5.3 above) and a value for K chosen to give a mean error factor of effectively unity. When the expression:

$$D = 1.438 \ q^{0.6}(1 + \beta)^{0.25} \frac{h^{0.15}}{d^{0.10}} \qquad \text{......} \ (5.15)$$

was used to process the results, the mean error factor was 0.9998 and the coefficient of variation of individual error factors was 26.8149%.

This result is very close to those from the model formula derived in Chapter 1, Section 1.4. It is better than any of the previous formulae tested, see Chapter 1, Section 1.3.

Figure 5.6 is a re-plot of individual error factors against W/D, using equation 5.15. It is plotted to the same scale as Figure 5.5 and it can be seen that using equation 5.15 the effect of W/D on depth error factor has largely disappeared.

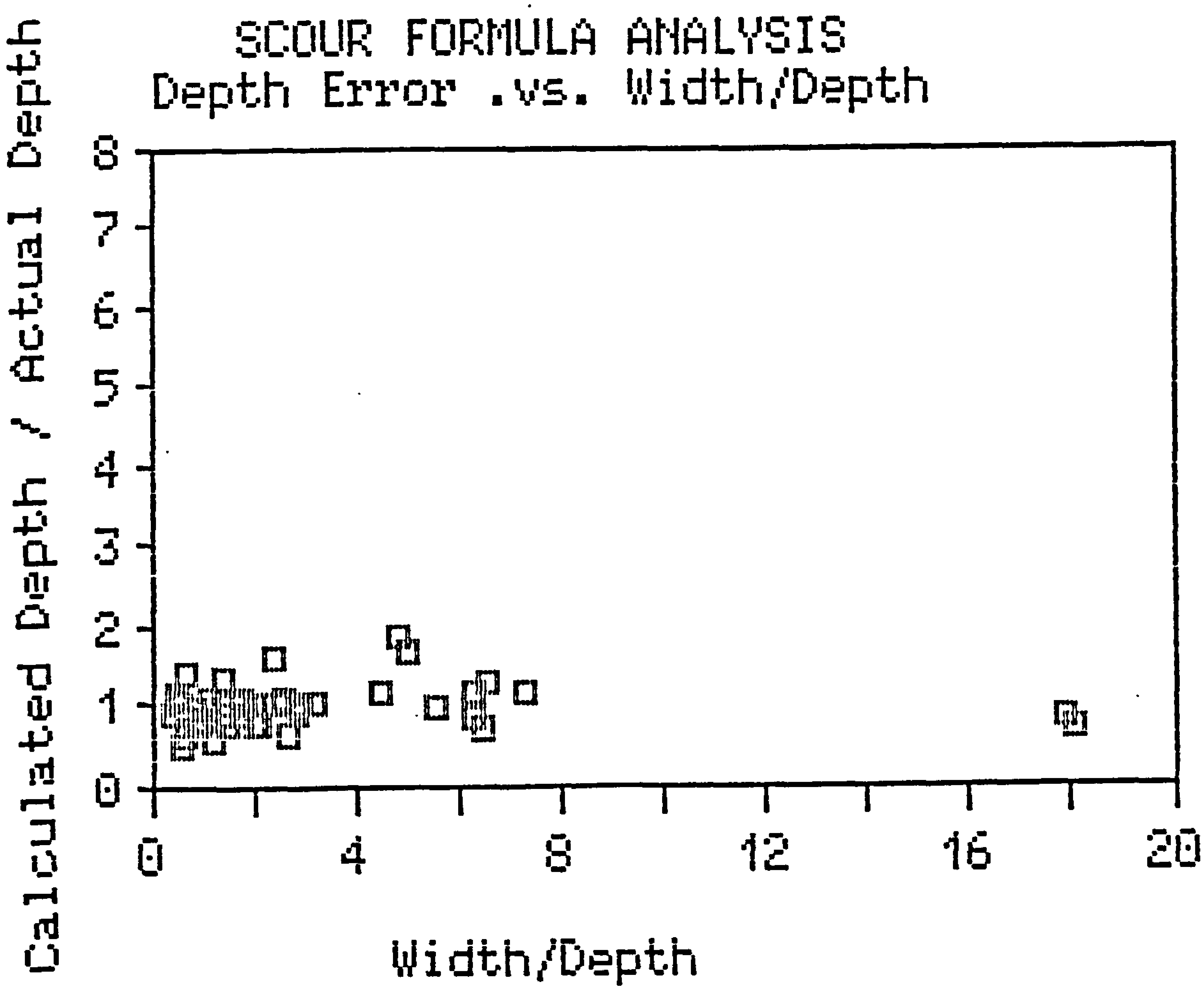


FIGURE 5.6 Depth Error Factors from Three Dimensional Equation 5.15 vs. W/D.

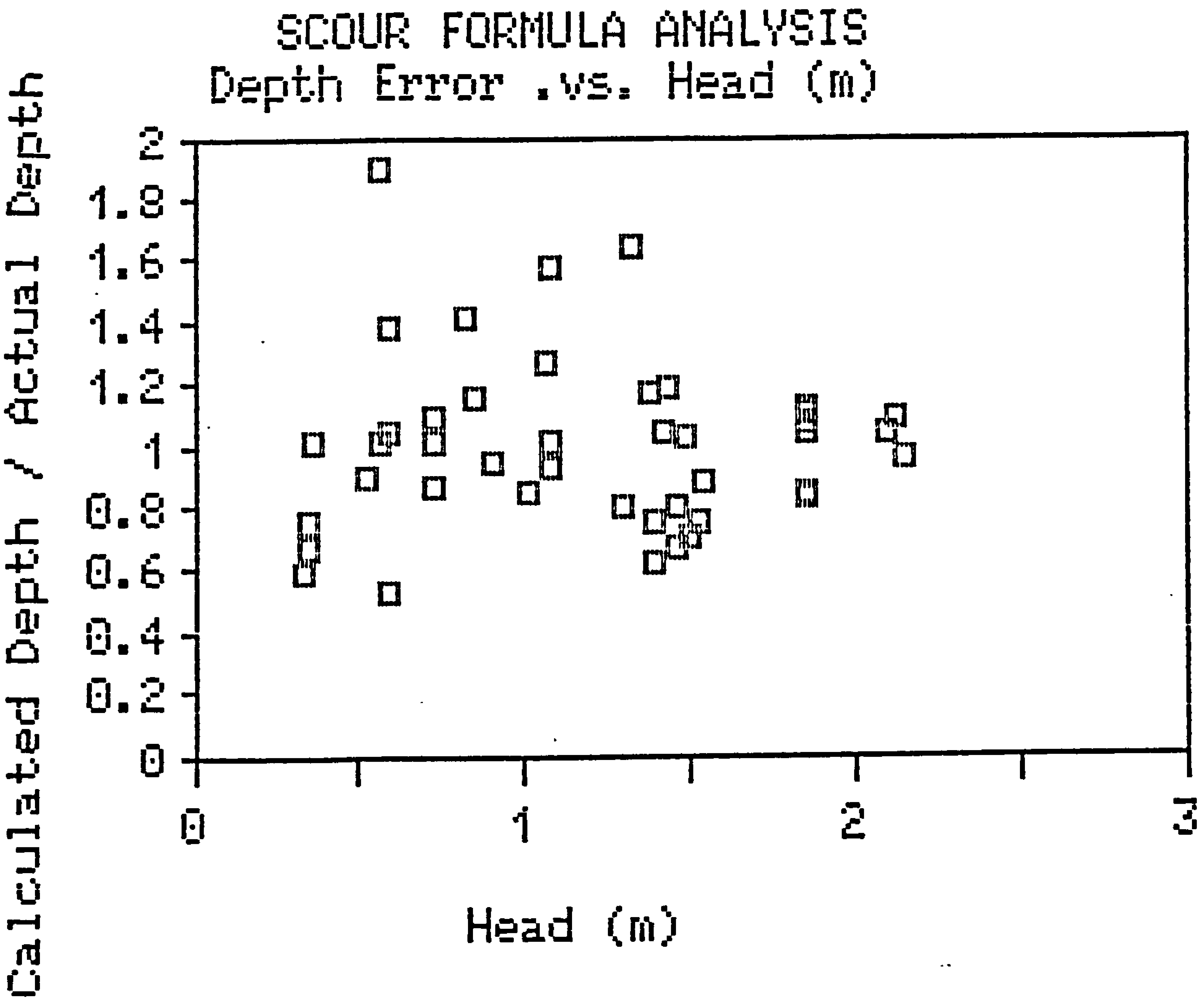


FIGURE 5.7 Depth Error Factors from Three Dimensional Equation 5.15 vs. H.

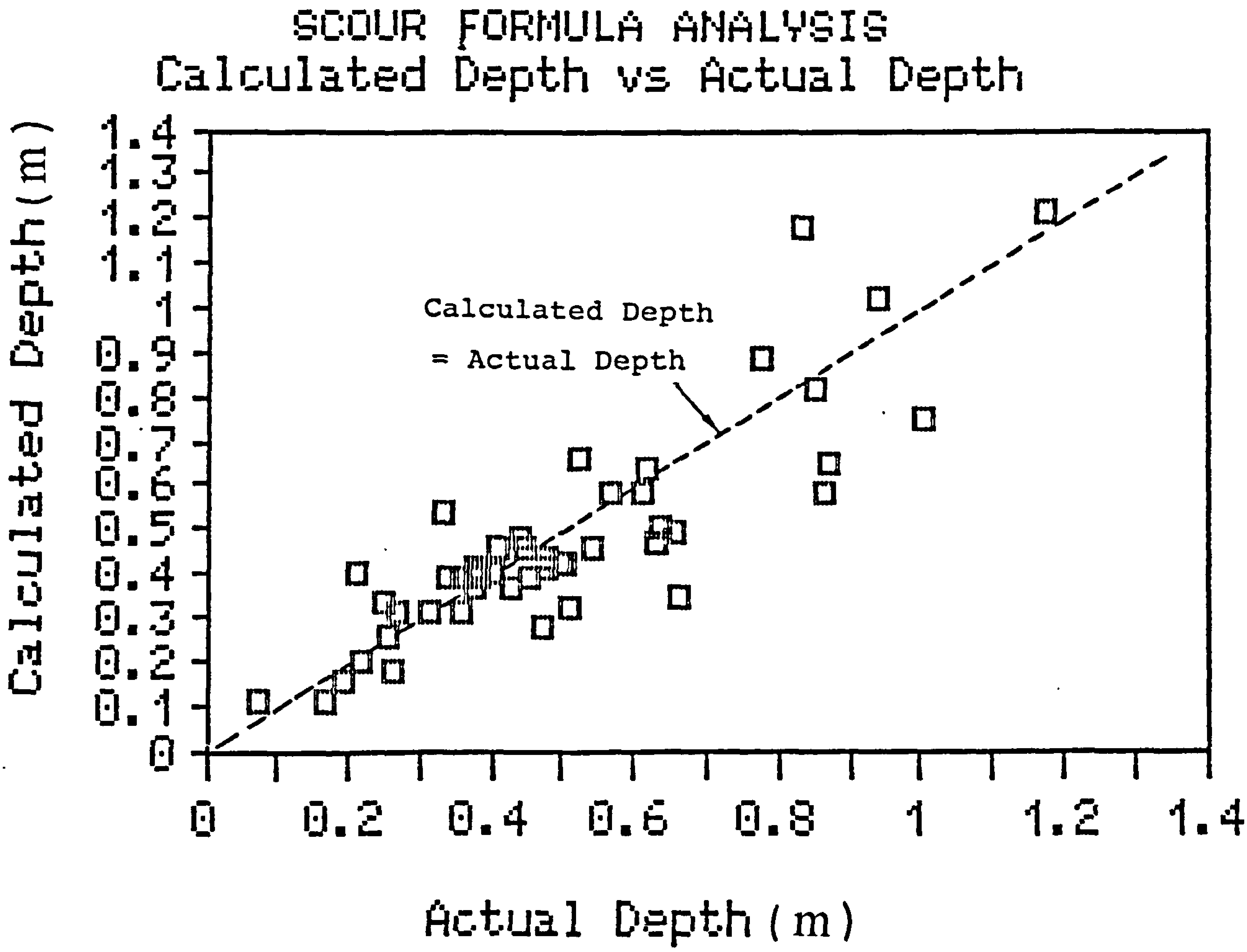


FIGURE 5.8 Depths calculated using Equation 5.15 vs. Actual Model Depths.

Equation 5.15, backed by and derived from the test results presented in Chapter 4 and as discussed in this Chapter, shows that scour depth can be calculated independently of head drop, H, other than allowing for the way in which H affects the air/water ratio β . It was mentioned in Chapter 2, Section 2.3.9 that the initiation of air entrainment is dependent on factors other than head alone and certainly at low heads there may be considerable variations in the value of β between different model arrangements. This could go a long way towards explaining the variations in the effect of head drop on scour proposed by previous authors. The actual effective variable should have been β rather than simply H. Figure 5.7 shows the error results from using equation 5.15 plotted against head drop H. It can be seen that the scatter is greatest for low values of H where one might expect greatest variance in air entrainment between models. As H increases the scatter decreases to a mean depth error factor of unity. Figure 5.8 shows the results of the above analyses using Equation 5.15 plotted in terms of D (calculated) vs D(actual).

It is recognised that at present research is lacking on air entrainment due to jets projected from ski jumps and flip buckets, even at a model scale. Ervine's expression strictly applies only to vertical falling jets but has been used here in the absence of anything else. Effects on aeration by other factors such as jet impact angle and spillway chute induced turbulence would also have to be quantified before expression 5.15 could be justifiably refined further.

CHAPTER 6

APPLICATION TO PROTOTYPES AND GENERAL SUMMARY

6.1 Application to Prototypes

6.1.1 Introduction

Applying any model test results to the erosion of scour holes in rock downstream of dams involves considerable uncertainties.

* It has to be assumed that the rock will break up and degrade such that it behaves like a non-cohesive material. This is considered by most writers on the subject to be a not unreasonable assumption and in fact is the basic assumption behind all model tests of such scour holes.

* It is generally assumed that aeration of flows on prototypes is greater than on models and that this affects comparisons between the two. This is discussed further in Sections 6.1.3, 6.2 and 6.3.

* Model measurements are generally made after a long period of constant flow has produced a stable scour pattern and depth. Flows associated with prototypes are usually the result of continually varying flood hydrographs and the assumption generally has to be made that the scour depth reached corresponds to the peak of the routed flood.

Given these uncertainties it was decided to apply equation 5.15 to a body prototype data to see if it could be extrapolated up to a large scale with any confidence.

One body of such data has been mentioned in Chapter 1, Section 1.3. It was assembled as Appendix B of the writer's previous M.Phil. Study (Mason, 1983).

A second set of data from one particular dam became available to the writer in January, 1987 when the writer was retained by B.C. Hydro of Canada to advise on the plunge pool scour development downstream of the Peace Canyon dam in British Columbia. Application of equation 5.15 to Peace Canyon dam is dealt with below in Section 6.1.2. Its application to a broader body of prototype data is dealt with subsequently in Section 6.1.3.

6.1.2 Peace Canyon Dam

Peace Canyon Dam comprises a 700 MW power station and a 116 m long gated spillway sited adjacent to each other in the main channel of Peace River. Earthfill flanks complete the dam. The dam gives a 40 m (approx) head drop to produce additional power and energy from releases through the much larger WAC Bennett Dam just upstream.

Turbine installation at the dam was phased such that after initial impounding in 1979 periodic releases had to be made through the gated spillway. This is essentially a gravity structure with a flip bucket at its base to deflect the flow in a free trajectory arc downstream. It was accepted that a scour hole would develop with time in the river bed. Model tests were carried out to determine the depth and extent of such a scour hole.

During the course of dam construction, horizontal, weak sliding planes were discovered in the shale foundations. This would, of course, have had serious implications for the sliding stability of the dam were they to 'day-light' through the upstream face of a scour hole immediately downstream. It was decided to deepen the foundations slightly but not to the full depth of the model scour hole (this would have been prohibitively expensive). It was decided that the model test results represented a hypothetical worst case which would be unlikely to be matched on the prototype.

In the event, scour progressed fairly rapidly in the first few years eventually exposing, locally, one of the weak sliding planes below dam foundation level. The writer was retained to visit Vancouver, to review the current status and history of the scour development and model tests and to advise on the likely depths and upstream limits of the hole for a range of flow options. The assignment was treated by the writer as a logical extension to this research study. The report prepared as a result of this assignment is attached to this study as Appendix C and should be consulted for further information.

The scour depth aspects of the study were carried out by making a comparison between:

a. Existing prototypes elsewhere in the world

b. The Peace Canyon model results.

c. Peace Canyon prototype measurements.

d. The writer's model formula as derived in Chapter 1, Section 1.4 of this study.

The result, in terms of a simple plot of scour depth against unit flow, is shown as Figure 1 of Appendix C, and reproduced here as Figure 6.1.

It should be noted that the writer's Section 1.4 model formula was used to process Peace Canyon Flows and produce the curves shown. The other, data, points plotted were not processed in this way and simply represent plots of scour depth against unit flow.

It was concluded by the writer as a result of this study that the model formula derived in Section 1.4, in fact represented a reasonable upper bound for prototype purposes. Also that the second, variable function expression in Section 1.4, proposed for model and prototype use, probably represented some rather anomalous prototype data.

In fact the assignment caused the writer to review the general prototype data assembled as Appendix B of the earlier M.Phil Study (Mason, 1983) and make certain adjustments in the light of further information. These will be discussed in Section 6.1.3 below.

In view of the findings in Chapters 4 and 5, the Peace Canyon information has now been re-calculated using equation 5.15. The results are given in Table 6.1 and are represented by an additional line superimposed on Figure 6.1.

There appears little to chose between the use of the Section 1.4 formula and equation 5.15. The former probably represents the best upper bound, overall. The latter represents arguably the best fit for the Peace Canyon model data and a reasonable upper bound for the majority of the prototype data. It should be noted that no Peace Canyon data was used in the analyses carried out in Chapter 5, Section 5.4.

6.1.3 Other Prototypes

In order to check equation 5.15 against a broader body of prototype data, the data assembled as Appendix B of the earlier M. Phil study was used. As mentioned in Section 6.1.2, a review of this data for the Peace Canyon assignment caused certain adjustments to be made. These are briefly mentioned below.

At the Grand Rapids Dam the previous flow intensity used assumed even gate operations. Further information revealed that the scour was associated with uneven gate operation. Exact flow intensities were not available and so two, upper and lower, extreme values were used to define a range. Where these points appear on Figures 6.2 and 6.3 a line is drawn between them.

Similar lines are drawn between the data points for Ghandhi Sagar, Hirakud and Panchet Hill dams where different sources have quoted different scour depths for similar flow intensities.

Q	q	H	β	h	D
50.000	13.286	40.843	0.9160	4.877	11.426
100.000	26.571	39.319	0.6550	6.401	17.391
150.000	39.857	38.405	0.5378	7.315	22.218
200.000	53.143	37.795	0.4679	7.925	26.415
250.000	66.429	37.186	0.4188	8.534	30.277
300.000	79.714	36.271	0.3795	9.449	34.057
350.000	93.000	35.662	0.3502	10.058	37.507

where

Q = Total spillway flow (cfs)
q = Spillway unit flow (m.m/s)
H = Head drop (m)
= Air / water ratio
h = Tailwater depth (m)
D = Scour depth below tailwater level (m) calculated using Equation 5.15

<u>TABLE 6.1</u> Scour Depth Estimates for Peace Canyon Dam using Equation 5.15

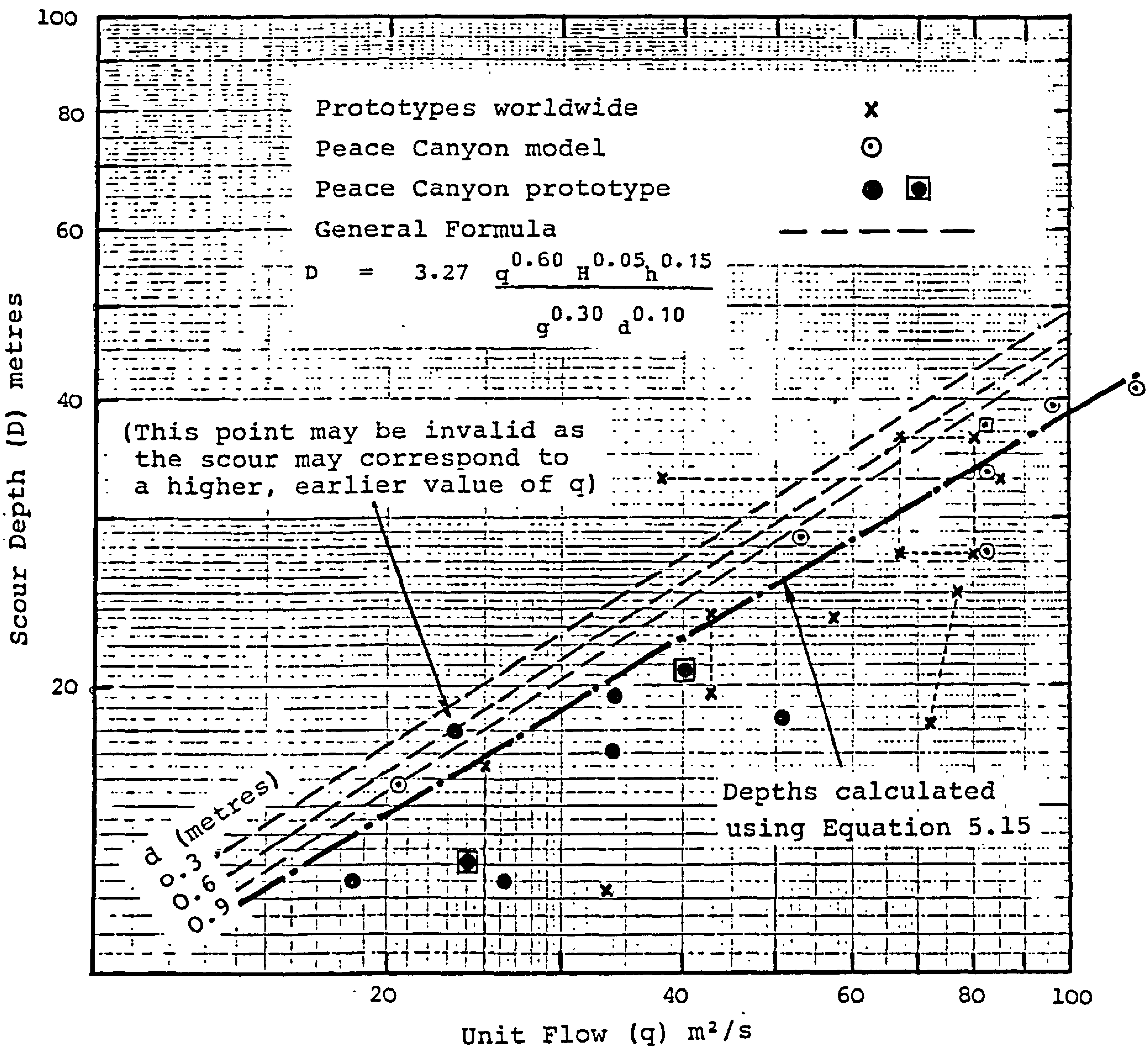


FIGURE 6.1 Scour Depth Comparisons for Peace Canyon Dam.

In the case of Jaguara dam it was found that the scour depths had inadvertantly been associated with the wrong unit flows. The depths were interchanged to remedy this.

A more detailed review of the Tarbela dam information caused the writer to abandon the data assembled for the Auxilliary Spillway. Additional published figures conflicted with the writer's earlier ones and the writer has been unable to establish which version is the correct one. Detailed information was available however for the Tarbela Service Spillway. A particular event occurred when it was apparent that stability had been reached. Short peak and longer term values for flow intensity were used in conjunction with general mean and local maximum scour depths. This gave in effect a range of four alternative combinations within which a realistic zone of depth against flow can be said to exist. This is represented on Figures 6.2 and 6.3 as four points, joined to form a rectangle.

All the prototype data used is given on Table 6.2. It is used to calculate scour depths in two ways. The first using Equation 5.15, the second using the Section 1.4 model Formula. The results of calculating prototype depths in these two ways, plotted against the actual recorded depths, are shown on Figures 6.2 and 6.3 respectively.

It can be seen that the results are broadly similar, though it is considered by the writer that the use of Equation 5.15 gives the best grouping of results.

Two outlying points in both cases are those for Kariba Dam where measured depths are significantly greater than those calculated. The jet arrangements at Kariba are complex with interacting jets converging downstream of the dam. This makes the definition of a unit flow at impact very difficult. Furthermore, Kariba dam has discharged many major floods over prolonged periods. There may, however, be

Dam	q	H	β	h	D (1)	D (2)	D (3)
G. Sagar	42.74	48.16	0.6093	13.20	25.603	31.623	19.510
	42.60	56.70	0.6826	13.20	25.839	31.819	23.870
Hirakud	72.46	32.00	0.3632	11.50	33.026	41.658	18.290
	77.30	39.70	0.4095	11.50	34.620	43.776	25.200
Maithon	33.40	40.84	0.6072	4.57	18.828	23.071	12.190
P. Hill	25.08	32.62	0.5907	6.02	16.481	20.021	8.080
	25.08	39.01	0.6684	12.00	18.497	22.403	16.450
G. Rapids	37.93	15.82	0.2967	4.00	18.878	23.278	32.960
	81.32	15.82	0.2112	4.00	29.328	36.785	32.960
Jaguara	57.14	34.00	0.4211	3.50	24.209	30.313	23.500
	148.00	37.00	0.2920	1.00	34.676	44.653	33.500
Picote	220.00	53.00	0.3134	30.00	73.564	96.054	54.000
Tarbela	66.46	109.00	0.8750	11.50	33.958	42.052	36.460
	66.46	109.00	0.8750	11.50	33.958	42.052	27.320
	79.40	109.00	0.8082	13.00	38.137	47.658	36.960
	79.40	109.00	0.8082	13.00	38.137	47.658	27.820
Alder	23.24	71.62	1.0496	3.50	15.464	18.339	28.350
Brazeau	2.36	58.22	2.5260	2.74	4.328	4.436	6.700
	4.17	58.22	1.9596	2.74	5.829	6.241	7.620
C Bassa	60.00	99.00	0.8577	29.00	36.606	45.218	42.000
	120.00	102.64	0.6453	42.10	56.920	72.610	67.100
Kariba	90.00	93.50	0.6884	14.00	40.868	51.557	88.000
	96.00	91.50	0.6591	16.00	43.152	54.617	90.000
Ottenstein	7.80	54.00	1.4075	7.00	9.278	10.421	12.000

where D (1) = Scour depth calculated using Equation 5.15
D (2) = Scour depth calculated using the Section 1.4 Formula
D (3) = Actual scour depth

<u>TABLE 6.2</u> Prototype Depths calculated using Equation 5.15 and the Section 1.4 Formula.

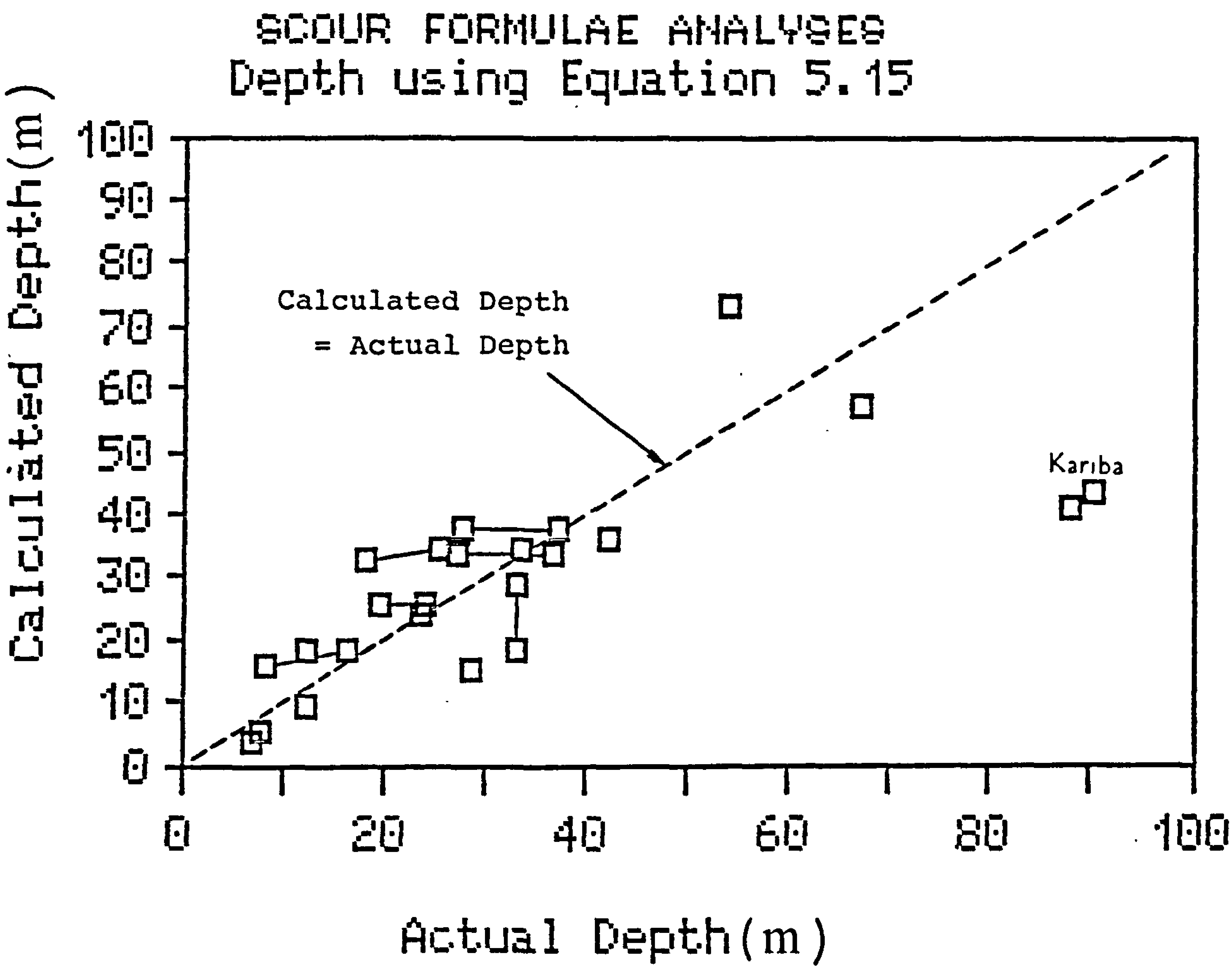


FIGURE 6.2 Depths calculated using Equation 5.15 vs. Actual Prototype Depths.

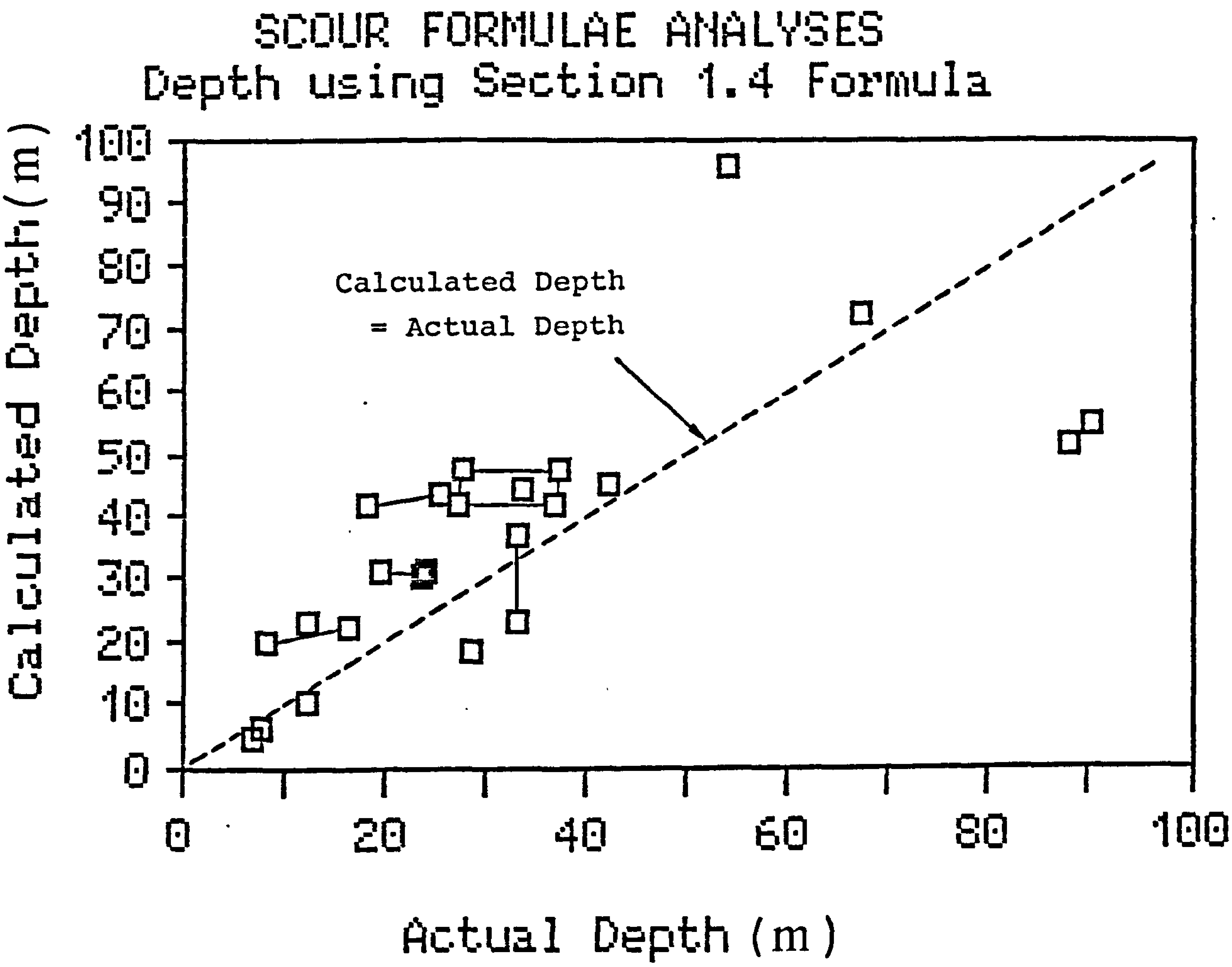


FIGURE 6.3 Depths calculated using the Section 1.4 Formula vs. Actual Prototype Depths.

another reason why scour depths are large. Equation 5.15 was developed on the assumption that the lateral extent of scour modified those forces from currents in the plunge pool which could be demonstrated for two dimensional scour. At Kariba, the sides of the plunge pool at depth are nearly vertical. This may serve not only to concentrate the jet but to create conditions nearer to the two dimensional case rather than the three dimensional one on which Equation 5.15 is based.

Given that Kariba may be an exceptional case, it is considered that Figure 6.2 demonstrates that Equation 5.15 can be extrapolated upwards for use with prototypes. This also has an interesting implication for protype air entrainment which may not be significantly greater than that which one might obtain on a reasonably sized model.

Aspects of air entrainment such as this will be discussed in the appropriate parts of Section 6.3 below. First it is perhaps worth presenting an overall summary of the results of this study and this is given below in Section 6.2.

6.2 General Summary

An earlier review by the writer (Mason, 1983) showed that the most popular and potentially accurate form of expression, to be used over the last 50 years for estimating scour under falling jets takes the form:

$$D = K \frac{q^x H^y}{d^z} \qquad \ldots\ldots\ldots(6.1)$$

although there is considerable disagreement between Authors concerning the value of y and hence the extent to which H affects the scour process.

A set of data was assembled from hydraulic model tests of various dams. By adjusting each variable in turn to optimise the accuracy of the result the following expression was derived:

$$D = 3.27 \quad \frac{q^{0.60} \; H^{0.05} \; h^{0.15}}{g^{0.30} \; d^{0.10}} \qquad \ldots\ldots (6.2)$$

It was surmised by the writer that the entrainment of air in plunge pools, by falling jets, could be a parameter affecting the scour process though what that affect was had hitherto not been quantified. Apparatus was built by the writer which allowed scour to be seen and measured as unit flow (q) and head drop (H) varied. Furthermore, the apparatus could exclude all air from the plunge pool or introduce air artificially in quantities that matched those which would occur were the jet to fall naturally through the air over a height (H). In order to ascertain what quantities of air should be introduced in this way a state-of-the-art review was carried out into air entrainment under jets. This concluded that the most appropriate expression on which to base air entrainment was that by Ervine (1976).

The results from carrying out two dimensional scour tests using the apparatus showed that, in the absence of entrained air, scour was independent of head drop (H) and directly proportional to flow, (q), such that in expression 6.1, $x = 1.0$ and $y = 0$.

The introduction of air, in quantities that a falling jet would entrain naturally, affected this result significantly. For the same range of head and flow values it was found that x varied from about 0.6 to 0.7 and y from about 0.03 to 0.2. These are very close to the values normally proposed for x and y in Formula 6.1 type expressions.

It can only be concluded that it is the degree of aeration produced by previous Author's models that have given previously proposed values for x and y. As aeration is not only a function of head drop but of other factors like jet width and internal turbulence it can be seen that not allowing for, or measuring, aeration as a separate parameter was bound to produce variable results.

From the results of the two dimensional testing it was concluded that stable scour conditions in the plunge pool were governed by the establishment of a characteristic force on the particles in the plunge pool. Scour depth was shown to vary with aeration to maintain this force. The expression obtained for two dimensional scour was:

$$D = 8.4 \quad q \quad (1 + \beta)^{0.5} \quad \frac{h^{0.15}}{d^{0.10}} \qquad \ldots\ldots \; (6.3)$$

It was also reasoned that the expression would have to be modified to allow for the lateral development of plunge pools in the three dimensional case. Also that such an expression would approximate to:

$$D = K \quad q^{0.5} \quad (1 + \beta)^{0.25} \quad \frac{h^{0.15}}{d^{0.10}} \qquad \ldots\ldots\ldots \; (6.4)$$

An analysis of the same set of model data as used to develop expression 6.2, produced the expression:

$$D = 1.438 \; q^{0.6} \; (1 + \beta)^{0.25} \; \frac{h^{0.15}}{d^{0.10}} \qquad \ldots\ldots\ldots \; (6.5)$$

It was shown to have a similar accuracy to expression 6.2 with most variation at low heads where the variation in air entrainment between models is likely to be greatest. It is concluded from all the results summarised above that expression 6.5, in fact, better describes the scour process than expression 6.2.

Lastly expression 6.5 was used to analyse a body of scour data from prototype dams and appeared to give acceptable results. It arguably produced better results than expression 6.2, used in conjunction with the same data.

It is concluded that expression 6.5 represents a new form of expression for calculating scour under jets, where air entrainment replaces the arbitary use of H as a factor defining the scour process. The expression seems to be applicable to models and prototypes and in the case of the former is at least as accurate as and probably more accurate than, any previous expressions developed to date. It is also concluded that any further work on similar scour formulae should now follow the findings of this study and incorporate an allowance for air entrainment if the results of such work are not to be essentially flawed.

One last interesting conclusion from this study is that air entrainment on prototypes may not be significantly different to those encountered on reasonably sized models, given that there may be an upper limit on β of around 2 to 3 and that such figures can easily be approached on models.

Further work is now needed on aeration of plunge pools downstream of flip buckets (as opposed to simple falling jets), to enable expression 6.5 to be refined further. This and other aspects are discussed in Section 6.3 below.

6.3 Suggested Areas for Further Research

There are several areas both on jet scour and aeration where further useful research could be carried out. These areas are therefore, by definition, potential sources of error in the present study. For simplicity they are presented below on a point by point basis, with brief discussions as appropriate.

* The effect of jet impact angle on scour was discussed in the writer's previous study (Mason, 1983), with inconclusive results. As it would appear from Chapter 2, Section 2.3.6 that impact angle may affect not only flow patterns in the plunge pool but also the degree of aeration produced, the matter as a whole could now be usefully reviewed and model tested.

* The Ervine (1976) Formula used to estimate aeration was derived from tests on falling, near vertical jets. Useful research could be carried out into how this varies when the jet is projected from a low level flip bucket in the form of a free trajectory arc.

* The effect on aeration of spillway chute induced turbulence would be interesting to quantify. It is often suggested in scour formulae that the value of (H) used should allow for spillway chute losses. If, however, this head loss has produced an associated turbulence in the jet which enhances aeration, such an arbitary adjustment may not be warranted. In carrying out the analyses in Chapter 5, Section 5.4 trials were carried out using (Hef) rather than (H) to calculate aeration. The differences in result were negligible.

* Further information is required on the entrainment of air by high velocity jets. The work by Van de Sande and Smith, (1973), see Chapter 2, Section 2.3.6 indicated that absolute velocity could affect entrainment. On the other hand it may be (Ervine, 1987) that there is a practical upper limit on β of about 2 or 3, see Chapter 5, Section 5.2. Also Ervine's formula (1976) implies similar values for β on prototypes as on large models and this seems to be born out by the writer's analyses of model and prototype scours.

* The effects on scour of particle size, shape, density and grading could also be usefully researched. Research to date has produced varying results and additional tests, without air as a variable, could produce more definitive information.

* Tailwater depth clearly has a variable effect on scour. The mechanism by which it does so would be useful to research and quantify.

* The effect of time on prototype scour, in conjunction with rock strength, is one of the most debated areas of plunge pool scour. A rigorous analysis of various prototypes will be needed before definite conclusions can be drawn. Indications to date are that in many cases scour progresses remarkably rapidly and for practical purposes time can be ignored as a parameter. In other cases such as Kariba where the plunge pool is in massive gneiss, analyses (Mason, 1985) suggest that time is a factor.

* The tests carried out by the writer were into two dimensional scour with results extrapolated to three dimensions. A new research study examining and model testing three dimensional scour could now be usefully undertaken.

APPENDIX A

SCOUR TEST RESULTS

The following tables comprise the principal results from the scour tests outlined in Chapter 4.

The results, in order are those of:-

- The non-aerated flow tests
- The rate of scour tests
- The aerated flow tests
- The artificially high and low aerated scour tests
- The varying tailwater tests

Symbols used are:

Q	=	Flow (l/s)
H	=	Head drop (h_3-h_2 on Figure 4.3)
d_1,d_2,d_3	=	Scour depth below datum (See Figure 4.3)
h_2	=	Tailwater depth (See Figure 4.3)
D_x	=	Scour depth below tailwater (= d_x + h_2)

TEST	Q (l/s)	H (m)	d1 (cm)	d2 (cm)	d3 (cm)	h2 (cm)	D1 (cm)	D2 (cm)	D3 (cm)
1-01	6.0	0.490	17.3	19.0	19.7	5.0	22.3	24.0	24.7
1-02	6.0	0.740	17.2	19.4	19.9	5.0	22.2	24.4	24.9
1-03	6.0	0.945	16.6	19.2	19.9	5.0	21.6	24.2	24.9
1-04	6.0	1.200	15.4	19.7	20.6	5.0	20.4	24.7	25.6
1-05	6.0	0.330	16.0	18.9	19.7	5.0	21.0	23.9	24.7
2-01	10.0	0.520	38.0	38.9	39.9	2.0	40.0	40.9	41.9
2-02	10.0	0.760	35.5	39.3	40.0	2.0	37.5	41.3	42.0
2-03	[Superseded by 4-01]								
2-04	10.0	1.240	34.2	41.8	43.0	2.0	36.2	43.8	45.0
3-01	7.5	0.505	24.8	27.5	29.1	4.0	28.8	31.5	33.1
3-02	7.5	0.745	25.7	29.3	31.1	3.5	29.2	32.8	34.6
3-03	7.5	1.000	25.2	29.5	30.7	3.5	28.7	33.0	34.2
3-04	7.5	1.245	24.2	28.5	29.9	3.5	27.7	32.0	33.4
3-05	7.5	1.645	22.7	27.0	28.5	3.5	26.2	30.5	32.0
4-01	10.0	1.000	38.0	41.5	44.6	2.0	40.0	43.5	46.6
4-02	3.0	0.490	12.8	13.6	14.5	0.0	12.8	13.6	14.5
4-03	4.5	0.495	16.8	17.7	18.6	2.5	19.3	20.2	21.1
4-04	4.0	0.740	14.0	15.8	16.9	2.0	16.0	17.8	18.9
4-05	5.0	1.000	16.0	17.4	18.8	3.0	19.0	20.4	21.8
5-01	9.0	0.745	32.5	36.0	37.9	2.5	35.0	38.5	40.4
5-02	9.0	1.250	30.0	35.9	37.8	3.0	33.0	38.9	40.8
5-03	10.5	1.745	35.0	41.4	44.3	2.5	37.5	43.9	46.8
5-04	10.0	1.995	32.8	40.3	43.8	2.5	35.3	42.8	46.3
6-01	10.0	1.645	32.0	38.5	41.6	5.0	37.0	43.5	46.6

RESULTS OF NON-AERATED SCOUR TESTS

TEST	Q (l/s)	H (m)	GATE GAUGE	TIME [mins]	SCOURED AREA [cm.cm]
3-01	7.5	0.500	1.00	1.0	322.5
				2.0	405.8
				5.0	462.5
				10.0	472.7
				20.0	556.5
3-02	7.5	0.750	0.72	1.0	346.0
				2.0	394.8
				5.0	433.4
				10.0	498.6
				20.0	561.6
3-03	7.5	1.000	0.55	1.0	353.4
				2.0	399.6
				5.0	469.8
				10.0	522.1
				20.0	606.5
3-04	7.5	1.250	0.40	1.0	320.6
				2.0	356.0
				5.0	441.2
				10.0	527.0
				20.0	582.8
3-05	7.5	1.650	0.25	1.0	322.8
				2.0	363.4
				5.0	421.4
				10.0	480.7
				20.0	532.1

[The scoured areas quoted are measured on the clear side of the tank and represent volume of material scoured]

RESULTS OF RATE OF SCOUR TESTS

TEST	Q (l/s)	H (m)	d1 (cm)	d2 (cm)	d3 (cm)	h2 (cm)	D1 (cm)	D2 (cm)	D3 (cm)
1-01A	[Not run , air too low for measurement by Rotameter]								
1-02A	6.0 [5.15]	0.750	23.0	23.7	25.5	3.0	26.0	26.7	28.5
1-03A	6.0 [6.58]	1.000	24.2	24.1	26.8	3.0	27.2	27.1	29.8
1-04A	6.0 [7.91]	1.250	25.1	24.1	27.6	3.5	28.6	27.6	31.1
1-05A	[Not run , air too low for measurement by Rotameter]								
2-01A	10.0 [4.74]	0.495	30.4	30.9	32.9	3.5	33.9	34.4	36.4
2-02A	10.0 [6.85]	0.750	31.7	33.3	35.7	4.0	35.7	37.3	39.7
2-03A	[Superseded by 4-01]								
2-04A	10.0 [10.49]	1.250	31.8	35.0	38.9	3.0	34.8	38.0	41.9
3-01A	7.5 [4.04]	0.490	25.1	27.5	28.7	4.0	29.1	31.5	32.7
3-02A	7.5 [5.83]	0.750	26.6	28.0	30.0	4.0	30.6	32.0	34.0
3-03A	7.5 [7.45]	1.010	28.7	30.0	31.7	3.0	31.7	33.0	34.7
3-04A	7.5 [8.95]	1.250	29.5	29.5	33.0	2.0	31.5	31.5	35.0
3-05A	7.5 [11.75]	1.650	31.7	31.3	34.5	2.0	33.7	33.3	36.5
4-01A	10.0 [8.73]	1.000	31.8	33.3	37.3	3.5	35.3	36.8	40.8
4-02A	[Not run , air too low for measurement by Rotameter]								
4-03A	[Not run , air too low for measurement by Rotameter]								
4-04A	4.0 [4.12]	0.745	17.7	17.2	19.3	2.5	20.2	19.7	21.8
4-05A	5.0 [5.95]	1.000	21.6	21.2	23.2	2.5	24.1	23.7	25.7
5-01A	9.0 [6.45]	0.740	29.2	31.7	34.5	4.0	33.2	35.7	38.5
5-02A	9.0 [9.89]	1.250	31.3	33.5	36.3	4.0	35.3	37.5	40.3
5-03A	[Not re-run with entrained air]								
5-04A	10.0 [15.23]	2.010	34.9	40.5	45.0	3.0	37.9	43.5	48.0
6-01A	10.0 [13.10]	1.650	34.0	38.3	42.7	4.0	38.0	42.3	46.7

[Flow figures in brackets represent air flow]

RESULTS OF AERATED SCOUR TESTS

TEST	Q (l/s)	H (m)	d1 (cm)	d2 (cm)	d3 (cm)	h2 (cm)	D1 (cm)	D2 (cm)	D3 (cm)
AA-35	10.0 [3.5]	1.010	32.3	35.0	37.8	5.0	37.3	40.0	42.8
AA-40	10.0 [4.0]	1.005	32.2	35.1	38.0	5.0	37.2	40.1	43.0
AA-200	6.0 [12.0]	0.750	21.0	21.5	23.8	5.0	26.0	26.5	28.8
AA-240	6.0 [15.0]	0.750	22.3	22.3	24.7	4.0	26.3	26.3	28.7
AA-300	4.0 [12.0]	0.745	13.3	13.4	15.2	3.0	16.3	16.4	18.2
AA-350	4.0 [14.0]	0.750	13.8	12.8	14.8	3.0	16.8	15.8	17.8
AA-400	3.0 [12.0]	0.495	10.4	10.6	12.4	2.0	12.4	12.6	14.4
AA-500	3.0 [15.0]	0.505	10.1	10.8	12.2	2.0	12.1	12.8	14.2

RESULTS OF ARTIFICIALLY HIGH AND LOW AERATED SCOUR TESTS

TEST	Q (l/s)	H (m)	d1 (cm)	d2 (cm)	d3 (cm)	h2 (cm)	D1 (cm)	D2 (cm)	D3 (cm)
303-125	7.5	1.000	26.6	30.1	32.5	3.0	29.6	33.1	35.5
303-170	7.5	0.985	30.1	33.0	35.6	2.0	32.1	35.0	37.6
303-225	7.5	0.990	34.5	37.2	40.4	1.0	35.5	38.2	41.4
303-270	7.5	1.000	38.1	40.9	43.7	1.0	39.1	41.9	44.7

[The second number in the test reference number is the depth below datum in mm . This plus h2 equals tailwater depth]

RESULTS OF VARYING TAILWATER TESTS

APPENDIX B

DATA FROM CASES OF MODEL SCOUR

Full details of the attached model test results are given in Appendix C of the writer's M.Phil Thesis (Mason, 1983). The hydraulic model test results quoted are those for the following dams:-

Code Letter	Dam	Country
Y	Al Massira Dam	Morocco
B	Brazeau Dyke	Canada
D	Brown Canyon Dam	USA
C	Cabora Bassa	Mozambique
E	El Cajon (Crest)	Honduras
F	El Cajon (L.L. Outlets)	Honduras
H	Hazelmere	S. Africa
I	Itaipu	Brazil
K	Kariba	Zambia/Zimbabwe
L	Lower Notch	Canada
N	Mudhiq	S. Arabia
Q	Picote	Portugal
S	Tarbela (Service S/way)	Pakistan
T	Tarbela (Aux. S/way)	Pakistan
V	Victoria	Sri Lanka

Code	H	Hef	Q	q	W	h	Dac	dm
Y	0.720	0.648	0.0493	0.0672	0.7336	0.280	0.427	0.0250
Y	0.720	0.648	0.0493	0.0672	0.7336	0.280	0.373	0.0230
Y	0.720	0.648	0.0493	0.0672	0.7336	0.280	0.353	0.0170
Y	0.720	0.648	0.0493	0.0672	0.7336	0.280	0.447	0.0170
B	1.456	1.092	0.0280	0.0093	3.0108	0.068	0.167	0.0190
B	1.456	1.092	0.0560	0.0165	3.3939	0.068	0.190	0.0190
B	1.372	1.029	0.1820	0.0746	2.4397	0.152	0.335	0.0190
D	0.350	0.336	0.0240	0.0294	0.8163	0.092	0.256	0.0010
C	1.520	1.368	0.1230	0.0934	1.3169	0.387	0.654	0.0280
C	1.385	1.246	0.2690	0.1848	1.4556	0.561	1.001	0.0280
E	1.842	1.750	0.0282	0.0704	0.3950	0.233	0.373	0.0260
E	1.842	1.750	0.0282	0.0704	0.3950	0.233	0.373	0.0210
E	1.842	1.750	0.0282	0.0704	0.3950	0.233	0.493	0.0160
E	1.842	1.750	0.0282	0.0704	0.3950	0.233	0.503	0.0160
F	1.845	1.661	0.0200	0.0993	0.2014	0.155	0.405	0.0260
F	1.845	1.661	0.0200	0.0993	0.2014	0.155	0.445	0.0210
F	1.845	1.661	0.0200	0.0993	0.2014	0.155	0.435	0.0160
H	0.551	0.441	0.0550	0.0540	1.0185	0.420	0.398	0.0055
H	0.551	0.441	0.0550	0.0540	1.0185	0.420	0.212	0.0055
I	1.010	0.808	0.2080	0.0614	3.3876	0.390	0.540	0.0040
I	0.890	0.712	0.3010	0.0887	3.3935	0.510	0.610	0.0040
I	1.065	0.825	0.4100	0.1207	3.3969	0.335	0.520	0.0040
I	0.840	0.672	0.6200	0.1827	3.3935	0.560	0.770	0.0040
K	0.584	0.555	0.0211	0.0632	0.3339	0.113	0.245	0.0105
K	0.584	0.555	0.0211	0.0632	0.3339	0.113	0.661	0.0071
K	0.517	0.491	0.0252	0.0504	0.5000	0.120	0.357	0.0053
K	0.585	0.554	0.0344	0.0689	0.4993	0.143	0.380	0.0053
L	1.076	0.861	0.0017	0.0101	0.1683	0.033	0.071	0.0080
L	1.076	0.861	0.0043	0.0251	0.1713	0.060	0.214	0.0080
L	1.076	0.861	0.0087	0.0503	0.1730	0.096	0.310	0.0080
L	1.076	0.861	0.0147	0.0855	0.1719	0.136	0.476	0.0080
N	0.325	0.309	0.0200	0.0364	0.5495	0.380	0.470	0.0140
N	0.341	0.324	0.0500	0.0909	0.5501	0.410	0.630	0.0140
N	0.345	0.328	0.0830	0.1509	0.5500	0.450	0.870	0.0140
N	0.341	0.324	0.0500	0.0909	0.5501	0.410	0.860	0.0020
Q	0.815	0.734	0.2055	0.4198	0.4895	0.462	0.831	0.0200
S	1.379	0.819	0.0990	0.0743	1.3324	0.033	0.507	0.0135
S	1.292	0.732	0.1980	0.1485	1.3333	0.053	0.633	0.0135
S	1.528	0.968	0.0990	0.0742	1.3342	0.187	0.473	0.0135
S	1.478	0.918	0.1980	0.1485	1.3333	0.236	0.617	0.0135
T	1.429	0.829	0.0990	0.0604	1.6391	0.057	0.263	0.0135
T	1.311	0.711	0.1980	0.1209	1.6377	0.175	0.328	0.0135
T	1.494	0.894	0.0250	0.0151	1.6556	0.221	0.259	0.0135
T	1.417	0.822	0.1980	0.1209	1.6377	0.297	0.564	0.0135
V	2.150	2.043	0.4450	0.1890	2.3545	0.350	0.850	0.0095
V	2.113	2.007	0.6420	0.2700	2.3778	0.413	0.938	0.0095
V	2.088	1.983	0.8400	0.3540	2.3729	0.475	1.175	0.0095

APPENDIX C

PEACE CANYON PROJECT DEFICIENCY INVESTIGATIONS

(Plunge Pool Scour)

B.C.Hydro
Vancouver, Canada

PEACE CANYON PROJECT
DEFICIENCY INVESTIGATIONS

Assessment of Probable Ultimate Extents of Plunge Pool Scour Downstream of the Spillway

February 1987

SIR ALEXANDER GIBB & PARTNERS

PEACE CANYON PROJECT

DEFICIENCY INVESTIGATIONS

ASSESSMENT OF PROBABLE ULTIMATE EXTENTS

OF PLUNGE POOL SCOUR DOWNSTREAM OF

THE SPILLWAY

SUMMARY

It is considered that for a flow intensity equivalent to a 200 000 cfs flood divided evenly between the 6 spillway gates, lowest scour elevations of 1 430 to 1 420 could be reached.

Should the flow intensity increase to that equivalent to a (say) 350 000 cfs flood divided evenly between the 6 spillway gates, lowest scour elevations of 1 390 to 1 380 could be reached.

The upstream profiles of such scour immediately downstream of the spillway buckets is likely to be characterized by a slope of 1V on 3.5H. The buckets should not be undermined, though no reliance should be placed on the rock downstream of the buckets when assessing their stability.

Monitoring of scour should continue to take place after any period of prolonged flood discharge or any change in gate operations. The high rock face along the right side of the plunge pool should also be monitored both in terms of erosion and movement. Should erosion of this face occur to an extent which allowed significant return currents to develop close to the spillway buckets, additional 3D hydraulic model studies might prove necessary. They are not considered to be necessary at present.

Efforts should be made to establish the depths of loose material believed to be present over areas of the plunge pool floor.

PEACE CANYON PROJECT

DEFICIENCY INVESTIGATIONS

ASSESSMENT OF PROBABLE ULTIMATE EXTENTS OF SPILLWAY

SCOUR DOWNSTREAM OF THE SPILLWAY

1. INTRODUCTION

This report summarizes work carried out as part of the Peace Canyon Project Deficiency Investigations. It presents the results of a consultancy study by P.J. Mason, representing Sir Alexander Gibb & Partners, Reading, England into the depth and extent of scour likely to occur in the river bed downstream of the spillway as a result of flood discharges. The work was carried out in the Vancouver offices of B.C. Hydro between 19th and 23rd January, 1987 and included a site visit on 20th January to witness test spilling through spillway bay No. 3.

2. BACKGROUND DATA

Various background data was made available including:

* B.C. Hydro Spillway Scour Status Report No. H.1879 of March, 1986.

* Hydraulic Model Test Reports of August 1970 (Western Canada Laboratories) and December, 1970 (La Salle Laboratories).

* Contour plots of plunge pool surveys made on 1st October, 1979, 15th April, 1980, 5th September, 1981, April, 1983, October, 1983 and 7-9th October, 1985, together with a composite plan based on the lowest levels recorded over all surveys.

* Details of the historic flow releases, made using the spillway.

* Tailwater and spillway gate discharge rating curves.

* B.C. Hydro, draft of inter-office memo Taylor to Stephenson dated 19th January, 1987 on Prediction of the Ultimate Scour Hole at Peace Canyon. (This included a provisional lowering of the routed PMF to a peak of 200 000 cfs (5 660 m3/s) pending further hydrological studies in 1987).

3. SITE VISIT

A visit was made to the Peace Canyon Project on 20th January, 1987 by the writer, accompanied by Messrs. Bell, Yung and Taylor of B.C. Hydro. Photographic and video records were made of discharges from bay 3 which spilled for about an hour at a rate of 25 000 cfs. Floating ice indicated that return currents behind the jet and close to the bucket were not strong, though such currents were impeded in any case by the remains of sheet piled coffer damming below bucket 3 and by the proximity of the rock boundary along the right side of the plunge pool. Strong currents were noticed by the right hand end corner of the powerhouse structure.

The single jet spread laterally to the right after deflection by the bucket.

4. RESULTS OF THE STUDIES

Scour assessment was carried out in two stages. The first was to establish the probable maximum depth of scour, the second an estimate of the likely upstream profile of the scour hole (i.e. the profile of the rock remaining immediately downstream of the buckets).

4.1 Scour Depth

Previous studies by the writer (1), (2), indicated that the dominant factor in plunge pool scour is the flow intensity or unit discharge. The approach used therefore was to plot scour depth (D) below tailwater level against unit discharge (q) and to make a comparison between:

a. Existing prototypes elsewhere in the World.

b. The Peace Canyon model results.

c. Peace Canyon prototype measurements.

d. Depths predicted by the writer's own scour depth formula.

The data points used in a., b. and c. above are given in Annexes A, B and C respectively. The writer's own formula (1), (2) was originally derived from model data but is now considered by the writer to be a reasonable upper bound extrapolation for prototype purposes. It is:

$$D = 3.27 \frac{q^{0.60} H^{0.05} h^{0.15}}{g^{0.30} d^{0.10}}$$

where: D = Max. scour depth below tailwater level (m)

q = Unit flow (m^2/s)

H = Head drop from reservoir level to tailwater level (m)

h = Tailwater depth (m)

g = Acceleration due to gravity (9.81 m^2/s)

d = Characteristic particle size (m)

The results of the comparison are shown in Figure 1 with formula estimates for bed particle sizes of 0.3, 0.6 and 0.9 metres:

It can be seen that there is a consistant pattern to all four approaches and that the curves derived by the formula give a reasonable upper envelope to the other points.

The curves are re-plotted as Figure 2 which shows them in terms of scour elevation against flow on the assumption that the flow is spread evenly between all 6 spillway bays. From Figure 2 it can be seen that at a flow of 200 000 cfs it would be reasonable to expect the scour hole to develop to the top of the sandstone layer at 1 430 level. If noticeable weaknesses occur in the rock immediately below that, the scour could progress further to, say, 1 420 level.

Similarly at a flow of 350 000 cfs, or an equivalent unit discharge, the scour hole could be expected to develop past the sandstone layer to approximately 1 390 level. Again if weaknesses occurred below that, the scour could progress to, say, 1 380 level.

4.2 Upstream Profile of Plunge Pool

Scour profiles are more difficult to assess than depth as not nearly as much research has been carried out into this aspect. Again four approaches were used and a comparison made between them. They comprised:

a. Profiles from model studies

b. Profiles from the prototype surveys

c. Upstream scour slope predictions using Taraimovich (3)

d. Upstream scour slope predictions using Chee and Padiyar (4)

The model study profiles were taken from the various scour results quoted in the December, 1970 report. The 200 000 cfs flood profile through 6 gates was assumed to be represented by the 233 750 cfs model flood through 7 gates (effectively 199 540 cfs through 6 gates. This featured a cohesive bed. The cohesive bed results for a 363 000 cfs flow through 6 bays could be used directly to simulate the larger flood. The results of a similar flow through 7 bays and on a non-cohesive bed were extrapolated down slightly to give an equivalent profile had the concentration been over 6 bays.

Results for 200 000 cfs and approx. 350 000 cfs floods are shown on Figures 3 and 4 respectively. In both cases existing prototype profiles have been added together with relevant estimates using the methods of Taraimovich and of Chee and Padiyar. The slopes predicted by these last two methods have been assumed to emanate from a point of maximum scour in line with the lower nappe of the jet projected linearly downwards from the point of impact with the tailwater. The incoming jet angle of 28^{o} was taken from model tests and the jet was assumed to impact with the tailwater at 0.9 of the theoretical throw distance from the end of the bucket.

The profiles shown on Figure 5, profiles A and B are considered to represent reasonable probable and lower bound estimates for long term scours associated with floods of 200 000 and 350 000 (approx.) cfs passing evenly through 6 gates.

The are shown with a slope of 1V on 3.5 H. This represents the general consensus slope of the model, prototype and Taraimovich profiles shown on Figures 3 and 4. The locations of the slopes are also based on approximate lower bound envelopes of these profiles.

The results suggest that the buckets should not be undermined. It is considered, however, that no reliance should be placed on the rock immediately downstream of the buckets for the purposes of stability calculations. Hydrodynamic forces able to remove the rock immediately above the scour profile shown would also be bound to affect the remaining rock to some degree, albeit by general loosening due to fluctuating, fissure pressurization. See also Section 5.3 on Monitoring.

5. ADDITIONAL AND SUPPLEMENTARY COMMENTS AND ASPECTS

5.1 General

The conclusions in Sections 3 and 4 above were drawn from reviews of prototype data from bays 3 to 6 and from model data and analyses which are applicable to all bays. In view of the consistency of the results it is considered that the conclusions drawn would be equally applicable to all six spillway bays.

5.2 Effects of Geology and Time

The results presented in Section 4 above assume that no significant anomalies or changes in geology will occur in the area of the plunge pool as the scour develops, though it is accepted that the rock may become progressively sounder with depth and that this may slow down the rate of scour.

The time taken for scour to develop is one of the most disputed aspects of plunge pool development. Clearly time and associated flow duration will be a factor in the development of maximum potential scour. Nevertheless it is considered to be normal International practice for major stability or dam safety checks, to assume that at some stage such extreme scours could develop.

5.3 Monitoring

Although from current data the scour envelopes presented on Figure 5 seem reasonable lower bounds for future development, it is considered prudent that monitoring be maintained and new scour depth surveys made after any period of prolonged or significant spilling or after any change in methods of gate operation.

The importance must also be stressed of monitoring the near vertical rock face to the right hand side of the pool. There have been cases where the lateral development of plunge pools has proved to be problematic. It is recommended that a photographic record be made of the face for future comparisons and that paint markings be made on the rock ledge or berm at approximately tailwater elevation, as a guide to assessing erosion development. It is also recommended that a survey monument be established at the top of the rock face adjacent to the deepest area of the plunge pool and monitored to check for long term movement.

Should erosion of the right side rock face occur to an extent which allowed significant lateral return currents to develop close to the spillway buckets, the situation should be reviewed. At that stage consideration should be given to further, 3D, hydraulic model testing to check on the security of the scour profile immediately downstream of the buckets.

5.4 Gate Operations

As a general principle it is normally considered best to operate spillway gates as evenly as possible, i.e. to minimize the difference in adjacent flows and hence avoid flow concentrations.

In the case of Peace Canyon the same principle should apply provided that this is considered acceptable from an operation viewpoint and that monitoring does not reveal the excessive development of local scour pockets at the foot of the high rock face to right of the pool or adjacent to the tailrace structure to the left. It is also important to monitor the effects on scour of any changes in gate operation procedures.

5.5 Additional Investigations

Although doubts have been expressed concerning the reliability of the earlier hydraulic model study results, they are generally consistant with what could have been expected and also with subsequent prototype behaviour. It is therefore not considered that any more would be learned at this stage from additional model studies, see however, Section 5.3 above.

The scour depth and profile studies described in Section 4, above made no allowance for loose material which may be covering the floor of the plunge pool. Although it is considered that the depths of such covering are likely to be small, nevertheless efforts should be made to establish what such representative depths are. This may be possible using geophysical techniques or may require direct exploratory inspection.

5.6 Bucket Stability

Although it is considered that the bucket should not be directly undermined by the pattern of plunge pool scour likely to occur, it is assumed that any future analysis will carefully review the stability of the buckets in terms of sliding and overturning. Any deflection of the buckets may rupture the waterbars at the top of the main spillway/bucket joints. The result would be to feed high head, centrifugal, dynamic pressures into this joint greatly increasing the risk of bucket failure. Should this occur, the steeply diving jet issuing from the downstream face of the spillway would lead to rapid and regressive erosion of the foundations, directly threatening the security of the main dam.

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ANNEXE A

SCOUR DEPTHS AT EXISTING PROTOTYPE DAMS

(Dams with bucket lip angles less than 45^o and generally moderate heads)

DAM	COUNTRY	LIP ANGLE	q (m^2/s)	D (m)	H (m)
Ghandi Sagar	India	31^o	42.74	19.51	48.16
		31	42.60	23.87	56.70
Hirakud	India	39	72.46	18.29	32.00
		39	77.30	25.20	39.70
Maithon	India	43	33.40	12.19	40.84
Panchet Hill	India	34	25.08	8.08	32.62
		34	25.08	16.45	39.01
Grand Rapids	Canada	20	37.93	32.96	15.82
		20	81.32	32.96	15.82
Jaguara	Brazil	34	57.14	23.50	34.00
		34	148.00	33.50	37.00
Picote	Portugal	28	220.00	54.00	53.00
Tarbela (Service)	Pakistan	30	66.46	36.46	109.00
		30	66.46	27.32	109.00
		30	79.40	36.96	109.00
		30	79.40	27.82	109.00

In the cases of the Indian dams two sources were used, the latter quoting deeper scour depths.

At Grand Rapids the two figures for q represent extremes with the probable q nearer the upper one.

At Tarbela, short term and longer term q values are given and general and local maximum scour depths, in order to give a general range of values.

ANNEXE B

PEACE CANYON MODEL SCOUR RESULTS

No. of Bays	Lip Angle	Flow (cfs)	q (m^2/s)	D (m)	H (m)	Bed
7	30°	363 000	82.06	37.80	38.0	Cohesive*
7	30°	90 000	20.42	15.85	41.5	Cohesive
7	30°	233 750	53.02	28.65	40.0	Cohesive
7	30°	363 000	82.34	33.53	38.0	Cohesive
7	30°	363 000	82.34	32.92	38.0	Non-cohesive
7	20°	363 000	82.34	27.43	38.0	(?)
7	20°	363 000	82.34	30.48	38.0	Cohesive
6	20°	363 000	96.45	39.62	38.0	Cohesive
5	20°	363 000	116.41	41.15	38.0	Cohesive

*The first result is from the Aug., 1970 tests using a bed material bound with cement. The remaining results are from the Dec., 1970 tests using non-cohesive beds and cohesive beds where the bed material was bound with bentonite.

ANNEXE C

PEACE CANYON PROTOTYPE SCOURS

Survey	Bays	Scour Level (ft)	Flow per bay (cfs)	q (m^2/s)	D (m)
Oct.79	3/4	1 460	33 000	51.04	18.59
Oct.79	5/6	1 480	17 000	26.28	12.50
Sept.81	3/4	1 460	22 000	34.10	17.07
Apr.83	3/4	1 452	22 000	34.10	19.51
Oct.83	3/4	1 454	15 000	23.22	17.98*'
Oct.85	5/6	1 475	12 000	18.58	12.50
-	3/4	1 450	26 000	40.13	20.73*2
-	5/6	1 475	15 600	24.08	13.10*2

In general the surveys were inspected and where a level reduction had occurred compared to the previous survey the depth D was calculated for the intervening flow q. Values of q are generally 5 to 6 day peak values.

*' This point may be false and the depth correspond to a higher, earlier value of q.

*2 These points represent maximum recorded values for D and longer term (12 day) values for q.

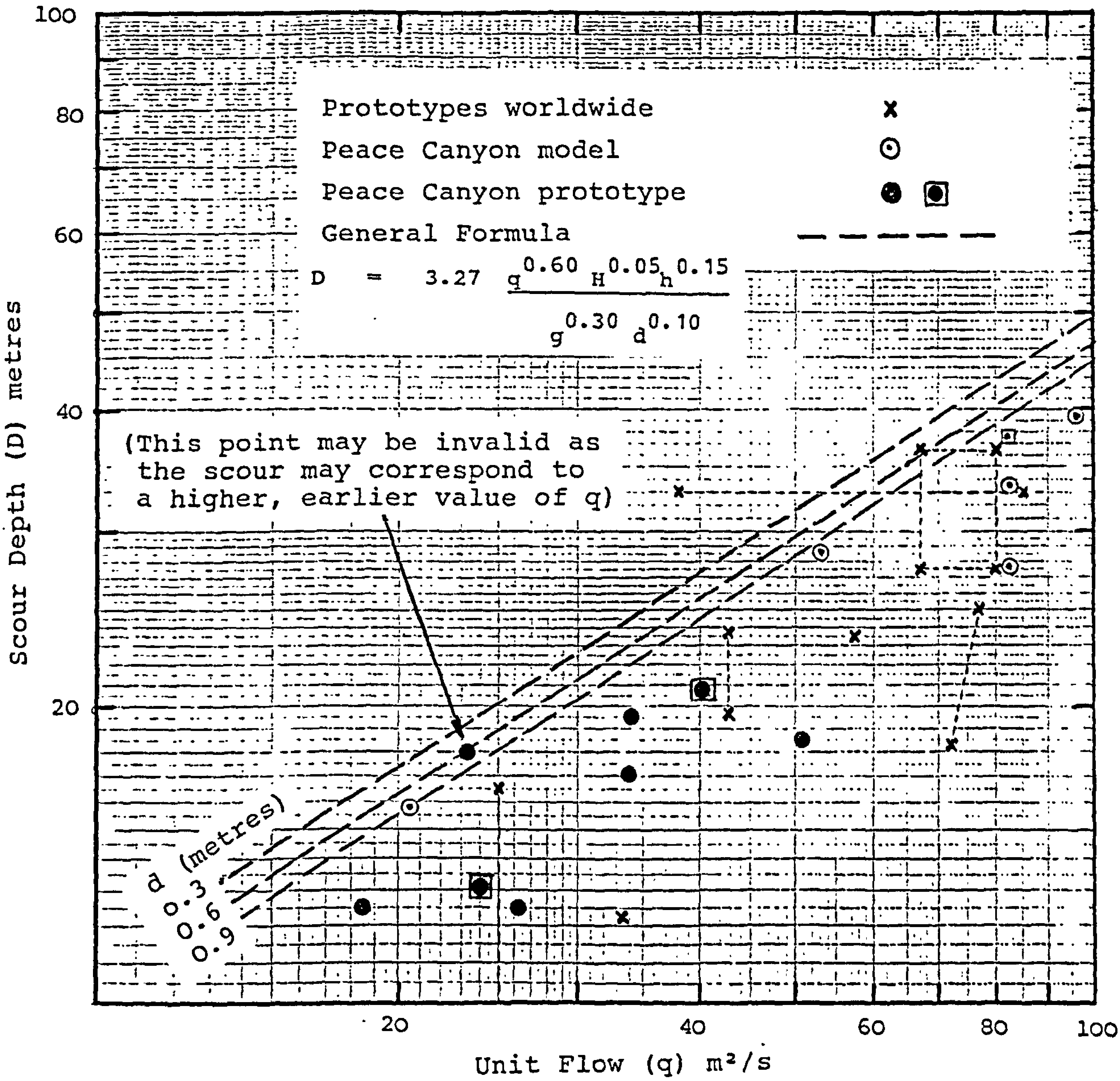
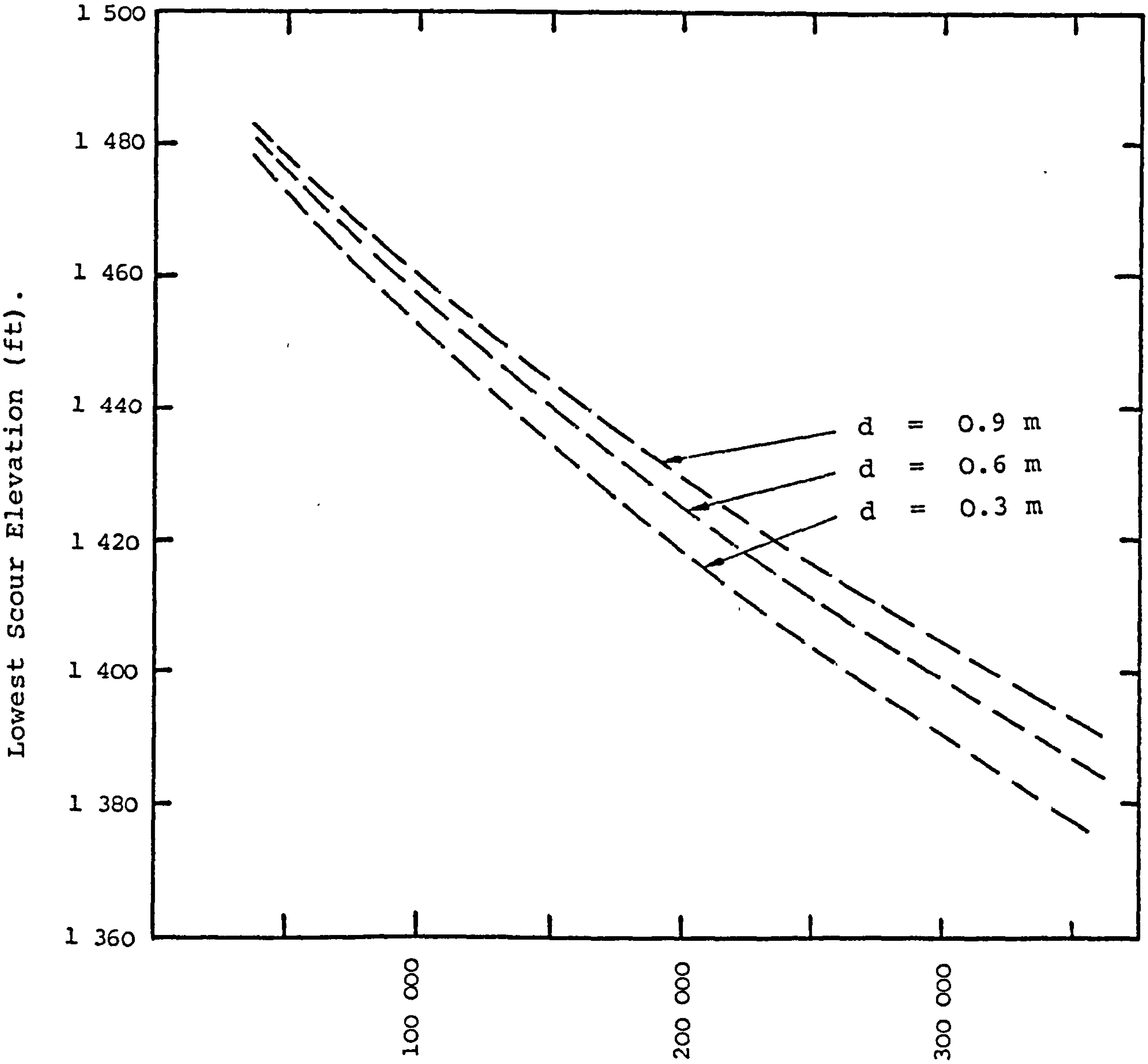


FIGURE 1

COMPARISON BETWEEN VARIOUS SCOUR DEPTH MEASUREMENTS AND ESTIMATES



Total Flow (cfs)
(Assuming Flow is evenly divided between all gates)

FIGURE 2
LOWEST SCOUR ELEVATIONS AGAINST
FLOOD FLOW, DERIVED FROM FIGURE 1

FIGURE 3
COMPARISON BETWEEN VARIOUS SCOUR
PROFILE MEASUREMENTS AND ESTIMATES
FOR A FLOW OF 200 000 cfs.

FIGURE 4
COMPARISON BETWEEN VARIOUS SCOUR
PROFILE MEASUREMENTS AND ESTIMATES
FOR A FLOW OF APPROXIMATELY 350 000 cfs.

FIGURE 5
ESTIMATED PROBABLE AND LOWER BOUND SCOUR PROFILES FOR FLOWS OF 200 000 AND APPROX 350 000 cfs DISTRIBUTED EVENLY THROUGH 6 DAYS

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